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ORIGIN AND DISTRIBUTION OF AEOLIAN SANDSTONES IN THE TRIASSIC CHARLIE LAKE FORMATION, NORTHEASTERN BRITISH COLUMBIA.

By

KELLY JAMES ARNOLD

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of Master of Science.

Department of Geology

Edmonton, Alberta

Spring 1994

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Origin and Distribution of Aeolian Sandstones in the Triassic Charlie Lake Formation, Northeastern British Columbia submitted by Kelly James Arnold in partial fulfillment of the requirements for the degree of Master of Science.

Dr. T.F. Moslow (Supervisor)

C.R. Stelck

Dr. C.R. Stelck

Dr. I. Campbell

Dr. N. Rutter

Date: Dec 20 /93

This thesis is dedicated to my Parents and Aunt, whom without their support and guidance this wouldn't have been possible. I would also like to dedicate it to my deceased Grandparents, Mary and Carl, who's dream it was to see this journey in my life fulfilled. Dreams do come true.

ABSTRACT.

Outcrop at the Brown Hill section on Williston Lake and 79 cores from the Inga Sandstone reservoir of the Late Triassic Charlie Lake Formation located in northeastern British Columbia have been described, interpreted and correlated. The presence of inverse graded laminations (wind ripple strata) and avalanche toes in the sandstones indicate an aeolian origin for the sandstones. Bounding surfaces and the distribution and proportion of aeolian stratification types in the sandstones infer the dunes to be obliquely oriented crescentic forms. The aeolian ergs prograded seaward on sabkha plains of the peritidal facies. Erg progradation was terminated due to a diminished sand supply during coastal onlap.

Correlation of the Charlie Lake strata from the Inga reservoir to the Brown Hill section by geophysical logs show two sandstone depositional horizons within the strata. The sandstones of the Brown Hill section are the western lateral equivalents to the lower sandstone horizon in the subsurface; the upper sandstone horizon is replaced to the west by the open marine carbonates of the Baldonnel sea moving down-section. The Baldonnel carbonates moving down-section coupled with the Halfway shoreline at the base moving up-section causes the Charlie Lake strata to wedge out toward the west.

Charlie Lake reservoir sandstones were deposited when dunes migrated into and filled structural basins likely associated with the Fort St. John Graben Complex. The basins establish depositional lows that preferentially preserve aeolian sands from reworking during marine transgressions. The porous sandstones are encased in tightly cemented marine-reworked sandstones and peritidal deposits. The various sandstone lithofacies produces a heterogeneous reservoir which affects vertical fluid flow within the reservoir. The most frequent and best quality reservoir lithofacies are high-angle cross-bedded sandstone produced by sand avalanching down slipfaces of dunes.

Additional sandstone reservoirs may be discovered east of the study area where erg migration was terminated early due to frequent transgressions causing short erg progradation from the source area. As well, sandy sabkha horizons in the Charlie Lake strata may represent the initial downwind (southwest) aeolian encroachment on a sabkha plain. If traced laterally upwind (northeast), these sandy sabkha horizons should grade into thick reservoir-quality aeolian sandstone. Another exploration strategy is to examine the structural framework within the Charlie Lake strata as each erg may have migrated through several basins creating a chain of reservoirs within each sandstone layer.

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As with any research endeavour of this type, completion would not be possible without the financial, technical, and moral support of many people and institutions.

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1.0.0 INTRODUCTION

The purpose of this study is to describe the sedimentology and stratigraphy of sandstones in the Late Triassic (Carnian) Charlie Lake Formation in northeastern British Columbia. The study involves Charlie Lake strata exposed in the Foothills area of Williston Lake and the subsurface Inga oilfield (Figure 1). Charlie Lake strata exposed in outcrop at Williston Lake, core from the Inga field, and geophysical logs between Williston Lake and the Inga oilfield provide the data base for this study.

The Charlie Lake Formation is a mixed siliciclastic-carbonate unit located in the Western Canada Sedimentary Basin and the Foothills of the Rocky Mountains. Red dolomitic siltstones, massive and interbedded anhydrites, microcrystalline to cryptocrystalline gray dolomites, shales, limestones, sandstones and a minor amount of salt (Gibson and Barclay, 1989) comprise the different lithologies in the Charlie Lake Formation. Solution breccias replace evaporites in the Foothills exposures. The sandstones, which are oil producing reservoirs, are continuous sheet like deposits making them difficult targets for petroleum exploration. The sedimentology of the Brown Hill outcrop section and the Inga interval of the subsurface, along with the outcrop to subsurface correlation, provide some strategies for exploration of additional sandstone reservoirs.

Within the study areas, the upper and lower boundaries of the Charlie Lake Formation are defined by the first and last occurrence of evaporitic units encountered within Triassic strata (Personal communication, Dave Robinson, 1991). This is not the case east of the study areas where evaporites occur within peritidal cycles of the Baldonnel Formation (Barss and Montandon, 1981). The sandstones within the Charlie Lake Formation were originally interpreted as "shoreface sand bars" encased in subtidal dolomites and evaporites, and intertidal siltstones and mudstones (Pelletier, 1965). The sandstones have recently been interpreted as aeolian dunes encased in lagoonal and sabkha deposits (Klein and Woofter, 1989; Higgs, 1990; Gibson and Edwards, 1990b; Woofter and MacGillivray, 1990).

1.1.0 Previous Work

The first work on Triassic stratigraphy was conducted on outcrop exposures in the Foothills of northeastern British Columbia by A.R.C. Selwyn of the Geological Survey of Canada in 1875. Selwyn's study was followed by Triassic studies by Dawson (1886) and McConnell (1891). The study of Triassic outcrop strata continued with the work of F.H. McLearn in the years between 1917 and 1948. McLearn's numerous reports were summarized in Geological Survey of Canada reports on the geology of northeastern British Columbia (McLearn and Kindle, 1950) and in McLearn (1953). Subsequent studies of

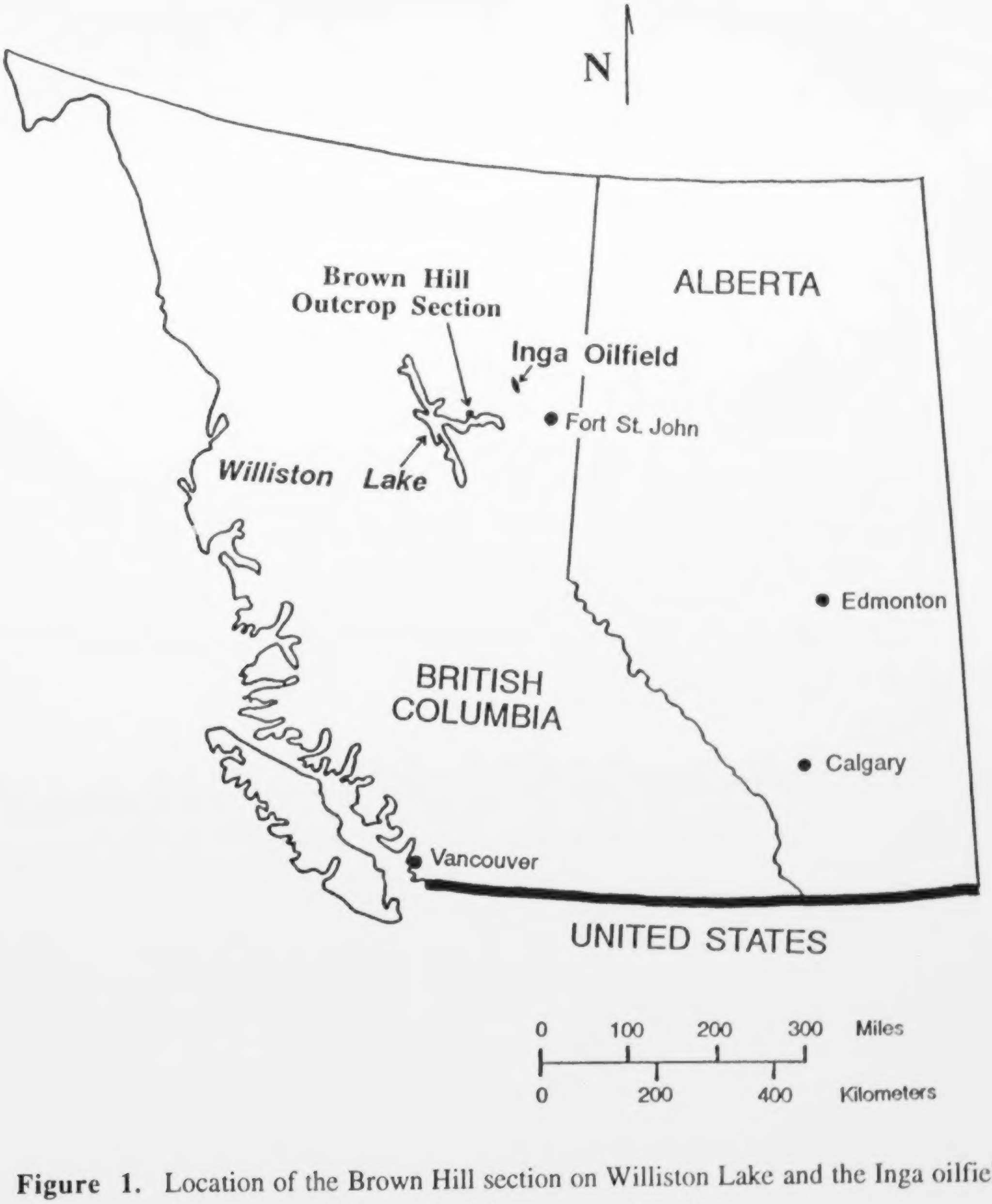

N
ALBERTA
Brown Hill
Outcrop Section
Inga Oilfield
Fort St. John
Williston Lake
Edmonton
BRITISH
COLUMBIA
Calgary
Vancouver
UNITED STATES
0
100
200
300
Miles
0
200
400
Kilometers

Figure 1. Location of the Brown Hill section on Williston Lake and the Inga oilfield study areas in northeastern British Columbia.

Triassic strata include Hunt and Ratcliffe (1959), Armitage (1962), Pelletier (1965), and Gibson (1971; 1975). The biostratigraphy of Triassic strata in northeastern British Columbia has been documented in studies by Warren (1945), Tozer (1961, 1967, 1982), and Siberling and Tozer (1968).

The name, Charlie Lake, was first introduced by L.M. Clark in an address before the Canadian Institute of Mining and Metallurgy in May, 1954, and applied to the evaporitic strata of the Upper Triassic (Hunt and Ratcliffe, 1959). The type section defined by Clark is located in the Pacific Fort St. John well No. 16, Lsd. 2, Sec. 18, T. 84, R 19, W. 6th Mer., near the town of Charlie Lake in northeastern British Columbia.

Hunt and Ratcliffe (1959) subdivided the Triassic into the Toad, Grayling, Halfway, Charlie Lake, Baldonnel and Pardonet Formations in a paper dealing with the correlation of Triassic outcrops in the Rocky Mountain Foothills to the subsurface of the Peace River area. They also placed the Halfway, Charlie Lake, Baldonnel and Pardonet Formations within the Schooler Creek Group. They cited the Charlie Lake Formation contacts with the underlying Halfway Formation and the overlying Baldonnel Formation as conformable.

Armitage (1962) introduced two new formations within the Triassic discussing the Triassic oil and gas occurrences in northeastern British Columbia. The Montney and Doig Formations are introduced replacing the Grayling and Toad Formations. The two new formations are also placed within the Daiber Group. Armitage (1962) cited oil production in the Charlie Lake Formation from the Boundary Lake Limestone and minor oil and gas occurring in "thin, stray, sandstone stringers". Armitage (1962) proposed that the Boundary Lake carbonate be formally adopted as a member of the Charlie Lake Formation.

B.R. Pelletier, in 1965, was the first to generally describe the sedimentary structures of the sandstones within the Charlie Lake Formation. In his paper on paleocurrents in Triassic outcrops of northeastern British Columbia he describes sandstones having cross-beds and festoons. He suggests an offshore sand bar for the origin of these sandstones.

The first study dealing specifically with the significance of the Charlie Lake Formation was by Fitzgerald and Peterson (1967). The paper is the first in depth discussion of the oil-producing sandstones of the formation and proposed the definition of new members based on the producing intervals. The lower Inga and upper Coplin sandstones were introduced as stratigraphic members within the formation. The general lithological description, contacts, facies correlations, general petrography, and reservoir structure and trapping mechanisms are dealt with. The authors claim the sandstones to be of marine origin, but no sedimentological evidence is given for this conclusion.

The first detailed sedimentologic description of the Charlie Lake Formation in the subsurface of northeastern British Columbia was by K.J. Roy (1972) who described the various lithofacies and their environments of deposition focussing on the Boundary Member. The Boundary Member consists of limestone with underlying anhydrite and overlying siltstones. Roy (1972) interpreted the limestones as lagoonal to intertidal in origin, the anhydrite as being deposited in a large standing body of water which periodically is subaerially exposed, and the siltstones as coastal plain tidal flats or sabkha deposits. A sandstone within the siltstone unit is discussed in the paper and used as a datum for the report. The sandstone is described as being fine to very fine-grained calcareous quartz arenite, 2 to 5 ft thick. The sand grains are rounded and frosted. He noted that the bedding is lenticular and ripple marks are present. The sandstone grades into anhydrite towards the west and dolomite towards the east. A depositional environment for these sandstones is not provided.

Klein and Woofter (1989) discussed the discovery and history of the Brassey oilfield of the Artex Member of the Charlie Lake Formation. The abstract is brief and focuses on the fields history but an interpretation for the sandstone is provided. The sandstone is interpreted as aeolian based on high-angle cross-bedding which is deposited within coastal plain dolostones and siltstones.

An abstract by R. Higgs (1990) deals with the sedimentology and petroleum geology of the Artex member. The aeolian interpretation of the sandstone is credited to Klein and Woofter (1989). However, Higgs adds to the interpretation suggesting the sandstone thicks represent dunes while the sandstone thins represent associated interdune areas. He also suggests a coastal setting for the dunes because of adjacent playa mud facies.

In a paper dealing with the development of the Brassey oilfield, Woofter and MacGillivray (1990) provide brief evidence for an aeolian interpretation of the Artex Sandstone. The sandstone consists of high-angle grainflow crossbeds, high to low-angle wind ripple laminations, contorted and massive sands and water lain interdune strata. Excellent core control indicates a primary wind direction from the north/northeast and a secondary wind from the northwest causing the aeolian dunes to migrate obliquely to the primary wind direction.

Recent Triassic stratigraphic nomenclature and depositional summaries are given by D.W. Gibson (1971 and 1975), Gibson and Barclay (1989) and Gibson and Edwards, (1990).

Gibson and Barclay (1989) and Gibson and Edwards (1990) suggest the Charlie Lake Formation sandstones were deposited as aeolian dunes and shoreface sands within a complex of arid coastal plain dolostones and siltstones.

1.2.0 Economic Significance

Triassic strata accounts for 4.6% of the in-place and recoverable conventional oil reserves in the Western Canada Sedimentary Basin (Podruski et al., 1988). There are 39 sandstone plays that have been discovered within the Charlie Lake Formation. These pools contain 22.57 million cubic metres of oil-in-place (Table 1). Podruski et al. (1988) predicts that there are an additional 68 undiscovered pools within the Charlie Lake Formation sandstones. These undiscovered pools contain an estimated 6.0 million cubic metres of oil-in-place with a predicted 0.3 to 0.4 million cubic metres of oil-in-place in the largest pool. The undiscovered plays are small, with the larger plays already having been discovered. The small size of the remaining plays necessitates the development of a geologic model to aid in the exploration for these undiscovered pools.

1.3.0 Unresolved Problems

There are few detailed published studies of the Charlie Lake Formation. Unfortunately these publications describe either the stratigraphy or the sedimentology of the Charlie Lake Formation carbonates. The publication by Fitzgerald and Peterson (1967) details the stratigraphy of the Inga sandstone with a brief description. The publication by Roy (1972) focusses on the Boundary Member of the Charlie Lake Formation which is dominantly of carbonate origin. To date, the economic sandstones of the Charlie Lake Formation have not been described in detail. There have been diverse origins assigned to the sandstones including shoreface bars, barrier islands, and aeolian dunes. A detailed sedimentologic study is needed to determine if the origin of the sandstones was shallow marine, aeolian or a combination of both. Without such a determination, it is impossible to create viable exploration or development models.

Reservoir sandstones in the Charlie Lake Formation are loosely refered to as "stray sandstones" (Armitage, 1962) because they randomly occur within the various other lithologies of the formation. Their random distribution is controlled by the sandstone origin and depositional cyclicity. Thus, an understanding of the origin of the sandstones can also determine their probable morphology, geometry and orientation.

Charlie Lake reservoir sandstones vary from 1m to 5m in thickness; pay zones within the reservoirs, however, vary from 0.5m to 3m. Other unresolved questions include: a) Do depositional processes control the size of the sandstone bodies and the size of their

Charlie Lake Sandstone Play

Pool Name	In-Place Pool Volume (million cubic metres)	Discovery Year
Inga-Inga A	8.75	1966
Inga-Inga	8.26	1966
Fort St. John A	1.41	1952
Cecil Lake North Pine A	0.79	1972
Boundary Lake Cecil B	0.59	1972
Two Rivers Siphon	0.58	1967
Cecil Lake A	0.46	1976
Boundary Lake Cecil A	0.43	1971
Cecil Lake North Pine C	0.39	1976
Stoddart Cecil A	0.19	1969
Cecil Lake Cecil C	0.16	1983
Squirrel North Pine A	0.16	1978
Eagle North Pine A	0.15	1977
Stoddart Cecil B	0.14	1976
Inga-Inga B	0.05	1980
16-19-85-23-Inga	0.04	1979
6-29-84-23-Inga	0.02	1982
Total Oil In-Place	22.57	

Table 1. Oil reserves of Charlie Lake Formation sandstone hydrocarbon pools in northeastern British Columbia (modified after Podruski et al., 1988).

reservoir potential?, b) What is the effect these processes have on reservoir quality parameters such as primary porosity, permeability, and cementation?; and c) Charlie Lake Formation sandstone bodies are thin, linear reservoirs, therefore, are the sandstones one continuous reservoir or are there several pools within each sandstone body?

The Charlie Lake Formation covers a large area of north-central Alberta and northeastern British Columbia (Figure 2). There may be lateral changes that occur in depositional environments and facies geometry and distribution from outcrop to subsurface. It is important to determine if the depositional environments vary from one location to another. Are the reservoir characteristics and sandstone trends observed in outcrops in the west the same as those observed in the subsurface in the east? For example, with the paleoshoreline in the west, the depositional environments of the sandstones proximal to the shoreline may be marine (barrier islands or shoreface bars), while the sandstones far to the east may be of aeolian origin. As a result, an outcrop derived depositional model may not be applicable to the subsurface reservoir sandstones. A correlation from the Foothills outcrops in the west to the Charlie Lake subsurface reservoirs in the east may provide insight to this question. However, a correlation of Charlie Lake Formation strata is difficult due to the thin interbedding of the different lithologic units. The various beds may pinch out or change abruptly or gradually into a different lithology. There are also problems of thrust faulting when constructing correlations through the Foothills in the west.

1.4.0 Objectives

The objectives of this study are:

1) To conduct a detailed sedimentological description of Charlie Lake Formation sandstones exposed in Triassic outcrop at Williston Lake in northeastern British Columbia using a process sedimentological approach. An outcrop exposure is preferred because it provides a complete section of the Charlie Lake Formation in which each sandstone unit can be examined. The sedimentary structures, grain size, ichnology, bedding contacts, and facies association are used to determine the origin and depositional environments of the sandstones. These sedimentary characteristics are best displayed in outcrop where the bounding surfaces, unit contacts, and facies changes can be laterally and vertically documented. The sedimentary facies and environments of deposition concluded from the observations are used to determine sandstone geometry, cyclicity and heterogeneity.

2) To conduct a detailed process sedimentologic description of the subsurface Inga Sandstone of the Charlie Lake Formation. The Inga Sandstone reservoir is ideal for this part of the study because it is an extensive sandstone body with a large subsurface database of well logs and core. The sedimentary structures, grain size, ichnology, bed contacts, and

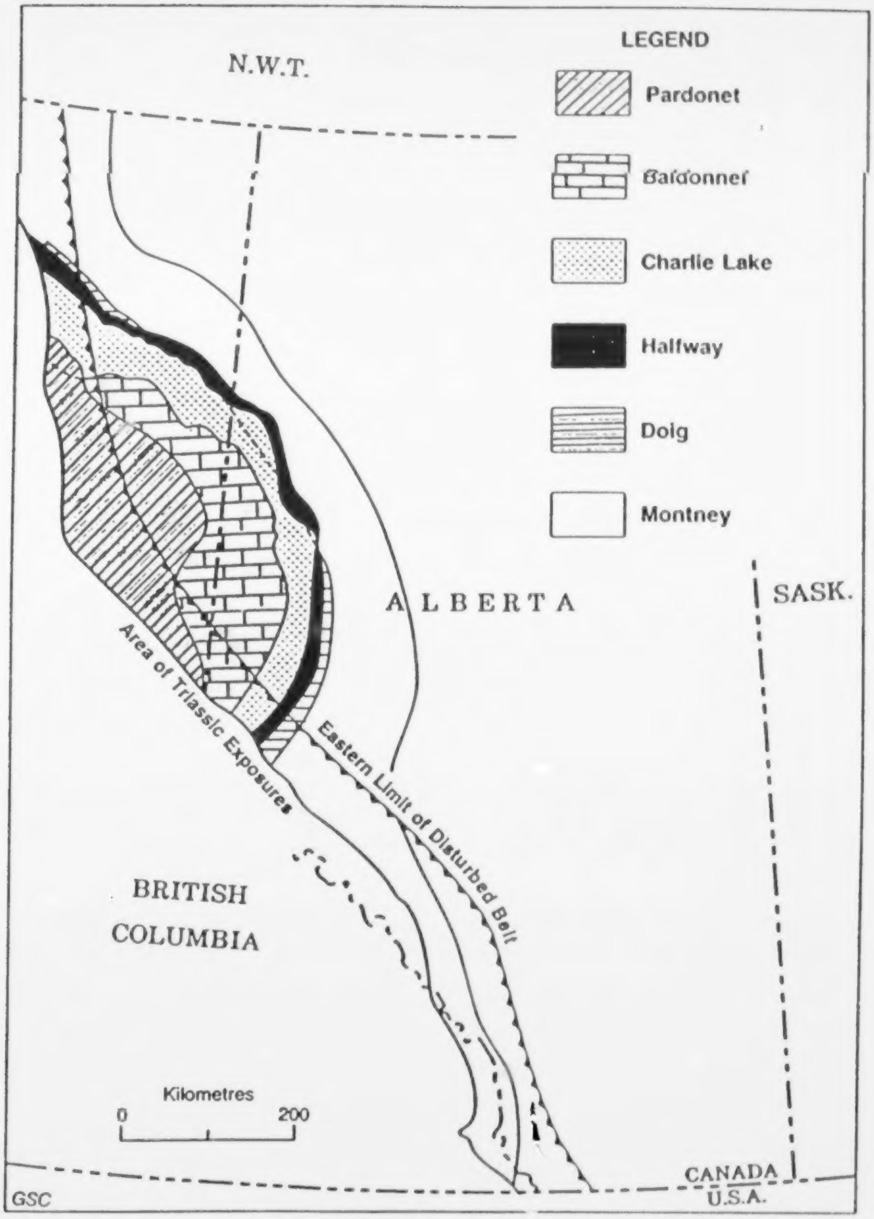

LEGEND
Pardonet
Baldonnel
Charlie Lake
Halfway
Doig
Montney
N.W.T.
ALBERTA
SASK.
BRITISH COLUMBIA
Area of Triassic Exposures
Eastern Limit of Disturbed Belt
Kilometres
0
200
CANADA
U.S.A.
GSC

Figure 2. Distribution of Triassic rocks in northeastern British Columbia and northwestern Alberta (modified after Podruski et al., 1988).

facies association are used to determine the origin and depositional environment of the Inga Sandstone. The lithofacies and environments of deposition obtained from the subsurface study are compared to the lithofacies and environment of deposition of the outcrop study. This determines if the model created from the outcrop can be used for exploration for sandstone reservoirs in the subsurface regionally.

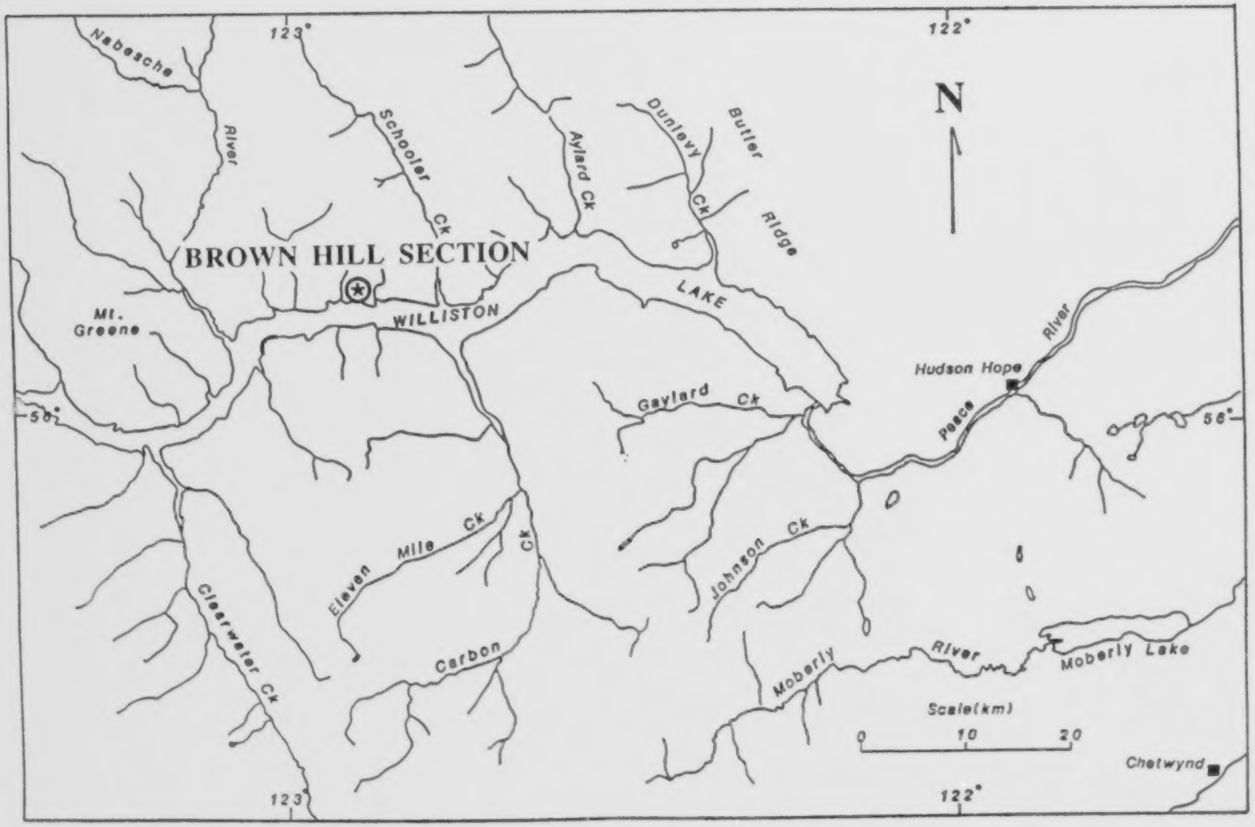
3) To determine the reservoir characteristics and facies correlations of the Inga Sandstone. This will lead to a model for the development of existing Charlie Lake sandstone reservoirs or for newly discovered sandstone reservoirs. The observed sedimentary facies are used to determine the lithofacies of best reservoir quality (porosity and permeability). To determine if the lateral and vertical extent of the reservoir body is continuous, or if there are permeability barriers or compartments within the sandstone that impede optimum oil recovery.

4) To provide a stratigraphic correlation of the Charlie Lake Formation strata from the Inga Oil Field area to the Charlie Lake strata exposed in outcrop at Williston Lake. This correlation will provide insight regarding the lateral extent of the sandstone bodies in outcrop into the subsurface of the Western Plains. The correlation may lead to the discovery of undetected sandstone reservoirs in the subsurface and provide insight into the relative age of the correlated strata.

1.5.0 Study Area

Strata of the Charlie Lake Formation are exposed in outcrops in the Foothills of the Rocky Mountains of northeastern British Columbia and western Alberta. The construction of W.A.C. Bennett Dam in 1967, along the Peace River, provides new and easily accessible reference localities for Triassic strata in the Foothills along the shores of the man-made Williston Lake. Access to the Williston Lake localities is best accomplished by boat in late May when the maximum rock exposure is highest due to the low level of the lake. Triassic strata at the Brown Hill (Figure 3) locality on Williston Lake is best suited for an outcrop examination of Charlie Lake Formation strata because it is continuous from the Lower Triassic Toad Formation to the Upper Triassic Pardonet Formation, is unfaulted, and contains several sandstone units within the Charlie Lake Formation interval. The annual rising and falling of the lake level keeps the outcrops clean, talus free, and fresh.

The Inga oil field is located approximately 50km northwest of the city of Fort St. John in northeastern British Columbia (Figure 1). The Inga field consists of Townships 84 to 88, Ranges 23 to 24, west of the Sixth Meridian (Figure 4). It is 67km long and 7km wide and is the largest oil accumulation in the Charlie Lake sandstones containing Initial Established



Nabesche
River
123°
Schooler Ck
Aylard Ck
Dunlevy Ck
Butler Ridge
122°
N
BROWN HILL SECTION
Mt. Greene
WILLISTON
LAKE
Hudson Hope
Peace River
56°
Gaylard Ck
Eleven Mile Ck
Ck
Johnson Ck
Clearwater Ck
Carbon
Moberly River
Moberly Lake
Scale(km)
0
10
20
Chetwynd

Figure 3. Location of the Brown Hill section where Charlie Lake Formation strata was examined at Williston Lake, northeastern British Columbia (modified after Gibson and Edwards, 1990).

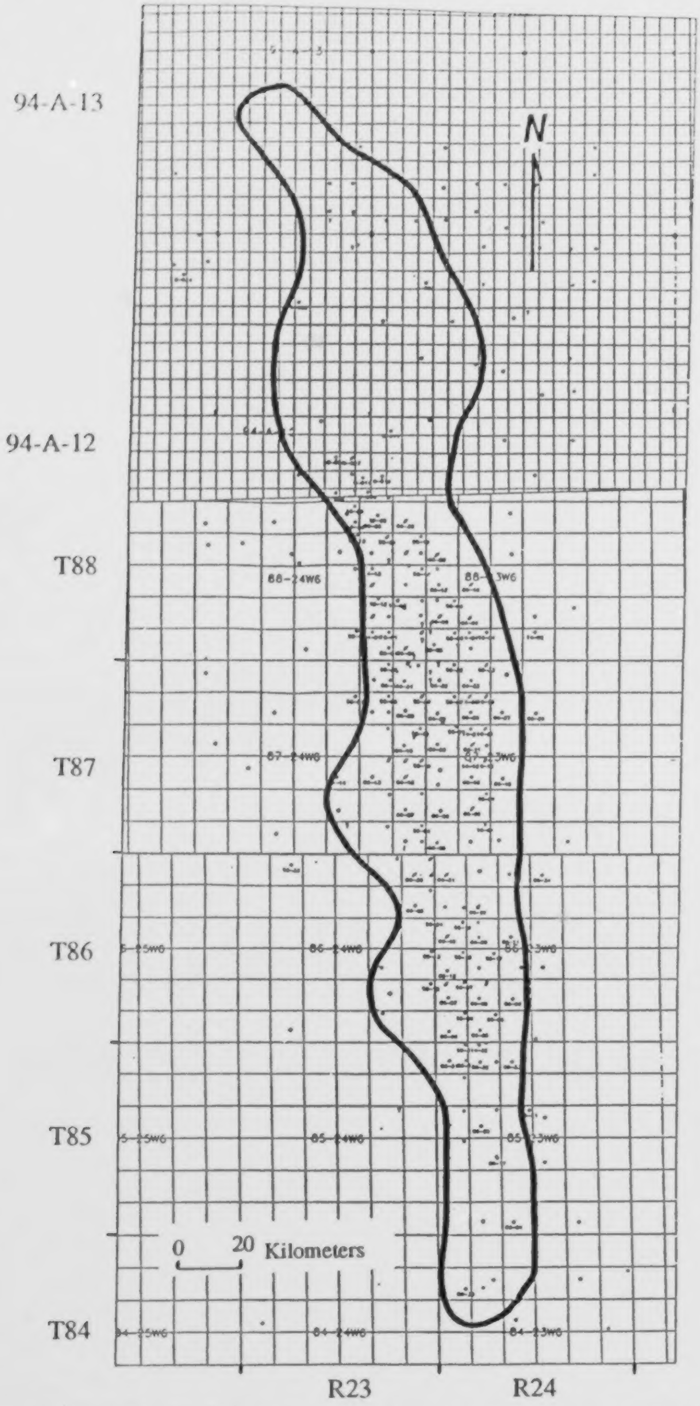

94-A-13
N
94-A-12
T88
88-24W6
88-23W6
T87
87-24W6
87-23W6
T86
86-25W6
86-24W6
86-23W6
T85
85-25W6
85-24W6
85-23W6
0
20 Kilometers
T84
84-25W6
84-24W6
84-23W6
R23
R24

Figure 4. Location of Inga oilfield and associated wells that penetrate the Inga Sandstone in the field. Cored wells are indicated with NTS and DLS location co-ordinates.

Reserves of 6,205 x 10^3 m^3 (Davies, 1992). The Inga oil field has a large database of some 190 wells, with 117 possessing geophysical logs and 112 are cored. The oil field has a well spacing of 1.6km, with 2 to 3 wells per section within the main field area. The cores vary in length from 8.5m to 37m but all of them penetrate the Inga Sandstone. The majority of the cored intervals are at least 18m long exposing the strata above and below the Inga Sandstone which aids in the interpretation of the Inga Sandstone and in correlations. Most wells contain an older but full suite of geophysicals logs consisting of spontaneous potential, resistivity, gamma ray, and sonic logs. Some wells have density logs.

There are 40 wells in the 75km distance between the Brown Hill section on Williston Lake and the Inga oilfield (Figure 5). These wells contain geophysical logs (spontaneous potential, resistivity, gamma ray, sonic, density) and penetrate the entire Triassic sequence. The wells will be used in the correlation of the Charlie Lake Formation strata in the 75km distance between the outcrop section and the Inga reservoir.

1.6.0 Methods

The outcrop location at Brown Hill on Williston Lake is accessible with a complete Triassic section and exposures of several sandstones within the Charlie Lake Formation interval. Sandstones of the Charlie Lake Formation in outcrop were described, sampled and photographed. As well, a gamma ray log was constructed of the outcrop section using a hand held gamma ray scintillometer. The Inga oil field was chosen due to its size, core coverage, and close proximity to the outcrop section in the Foothills. The Inga Sandstone in core was sedimentologically described, sampled, photographed, and correlated to geophysical logs. The subsurface Charlie Lake Formation was correlated to the outcrop section using geophysical logs from 40 wells located between the two sites in the study areas.

1.6.1 Outcrop Description

The Brown Hill outcrop section is located on the north shore of Williston Lake (Figure 3). The Triassic strata at the section is 800m thick starting in the Toad Formation (Gibson and Edwards, 1990) and ending in the Pardonet Formation. The strata dip at 72 degrees to the SSE with a strike of 170 degrees. The lateral extent of the outcrop is approximately 20m with the lake bounding one end, and the tree line bounding the other. The outcrop description for this thesis starts in the grey beds of the Liard Formation and ends in the overlying Baldonnel Formation. This ensures that both contacts of the Charlie Lake Formation are described, as are the facies and related depositional environments of the underlying and overlying formations.

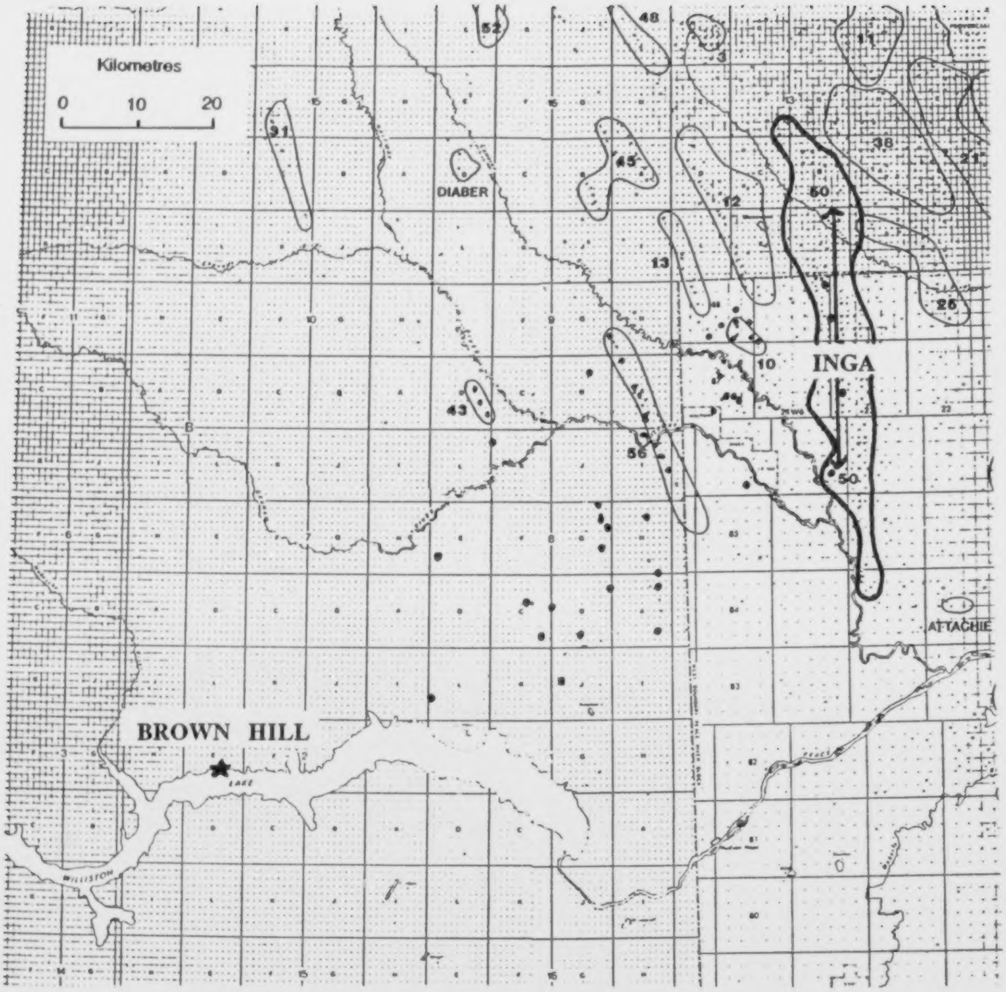

Kilometres
0
10
20
52
48
3
11
31
45
DIABER
38
21
50
12
13
25
10
INGA
43
56
50
ATTACHIE
BROWN HILL
WILLISTON
LAKE

Figure 5. Map showing the location of the 40 wells penetrating the Charlie Lake strata between the Brown Hill and Inga study sites.

Sedimentary characteristics of lithofacies described include:
1) nature of bed contacts (upper and lower)
2) sediment composition and percentage
3) sediment texture (size and sorting)
4) physical sedimentary structures
5) biogenic sedimentary structures
6) fossils
7) bed and unit thickness

Lithofacies were described both vertically and horizontally. This procedure is used to determine if there are any changes laterally or vertically in sedimentary structures, composition and texture. Samples and photographs of various units were taken for further examination. A sedimentologic strip log of the described section summarizes the sedimentary characteristics of the various lithofacies examined.

The exposed sandstones of the Charlie Lake Formation were sectioned in 2m by 2m grids to allow a detailed description and illustration of the sedimentary features. Sedimentary structures, such as cross-bed bounding surfaces, were traced and then plotted on diagrams. The various strata within each cross-bed, plane bed, and massive sandstone bed were described and plotted on the diagram. The gridding of the sandstones allowed the construction of detailed diagrams showing the various internal sedimentary structures, lateral geometries, and the nature of the contacts of each sandstone bed. This procedure aided in determining the origin and depositional environments of the sandstones.

1.6.2 Hand-held Gamma-Ray Scintillometer

The lightweight, portable Scintrex GIS-5 integrated gamma-ray spectrometer is used for gamma-ray readings from outcrop. This instrument has the capability of measuring either total radiation or individual (K-Th-U) radioelement concentrations (Myers and Wignell, 1987). The recording diameter of the instrument equals 0.3m, so that gamma-ray measurements made on thinner beds will be influenced to some degree by gamma-radiation from adjacent strata. Total radiation measurements were made at 0.6m (2ft.) intervals as suggested by Slatt et al. (1992).

Gamma-ray readings were taken from the lithologically described Triassic section at Browns Hill. Five total count readings, for three seconds each, were taken for each stratigraphic horizon sampled. The highest and lowest values were discarded and the three remaining values were then averaged to obtain a sample value for that interval. In total, 379 intervals were sampled at the Brown Hill section. The data was then plotted on a gamma-ray log creating a standard well log curve as a function of stratigraphic depth. The outcrop gamma-ray log can be used for correlations to subsurface gamma-ray logs.

1.6.3 Core Description

The procedure and methods for describing a cored sequence is the same as that used for describing a stratigraphic section in outcrop. Unfortunately, due to the small diameter of the core, the sedimentary characteristics can not be observed laterally. Core was described using the format and procedures outlined by Siemers and Tillman (1981). The description format employed in this study ensures that the cores are completely and consistently described, and allows a comparison to be made between different described wells. The information is recorded on core description sheets at a scale of 1:30. The plotting of the description on sheets provides a visual summary of the core and its sedimentary characteristics. The core description sheets for the subsurface Inga Sandstone are contained in Appendix A.

1.6.4 Process Sedimentology

A process sedimentological approach was used to describe the Charlie Lake Formation strata in outcrop and with the cores of the subsurface Inga Sandstone. This approach attempts to understand the origin of a sedimentary deposit through the observation of details and genetic units in a vertical and lateral sequence (Siemers and Tillman, 1981). Genetic units are "lithological units that display features which originated from processes that were relatively constant or varied in a uniform manner, throughout the formation of those lithologic units" (Siemers and Tillman, 1981). Process sedimentology delineates the physical, biological and chemical processes that occurred to generate the sedimentary product. Knowledge of the processes, combined with information such as the local and regional character and distribution of lithofacies, paleontology, and basin tectonics, can be used to generate a predictive sedimentary model that accounts for all of the available data as opposed to attemping to make the data fit a pre-existing depositional model.

1.6.5 Log Correlations

The gamma ray and neutron-density logs were the main logs used for correlations within the subsurface Inga reservoir and from the reservoir to the outcrop section at Williston Lake. Gamma ray logs measure natural radioactivity in formations and therefore are usefull for identifying lithologies and aid in correlations. Shale-free sandstones and carbonates typically have low concentrations of radioactive material giving low log readings. As the shale content increases so does the log response. The combination neutron-density log measures porosity of a formation with the density log recording the electron density and the neutron log recording the hydrogen ion concentration of a formation. The combination log is also used to determine lithology and gas-bearing zones. An example combination gamma ray neutron-density log is shown in figure 6. The logs are useful in correlations dealing with mixed siliciclastic-carbonate strata because they allow the recognition of the various lithologies and are useful in correlating the lateral lithofacies relationships of the strata over large distances. The cored intervals of the wells were also compared with the log curves to further the accuracy of the lithologies indicated by the logs.

1.6.6 Sampling and Photography

Hand samples were collected from the various sandstones, and overlying and underlying rock units in the outcrop section. One sample was collected from each lithofacies examined for further study (description), petrography, and for photography. Small samples of the Inga Sandstone were cut from selected cores for petrographic study of the sedimentary structures (ie, inverse grading), grains, and composition of each facies. Photographs of the sedimentary structures and contacts were taken to allow a later comparison of units and features seen in different sandstones.

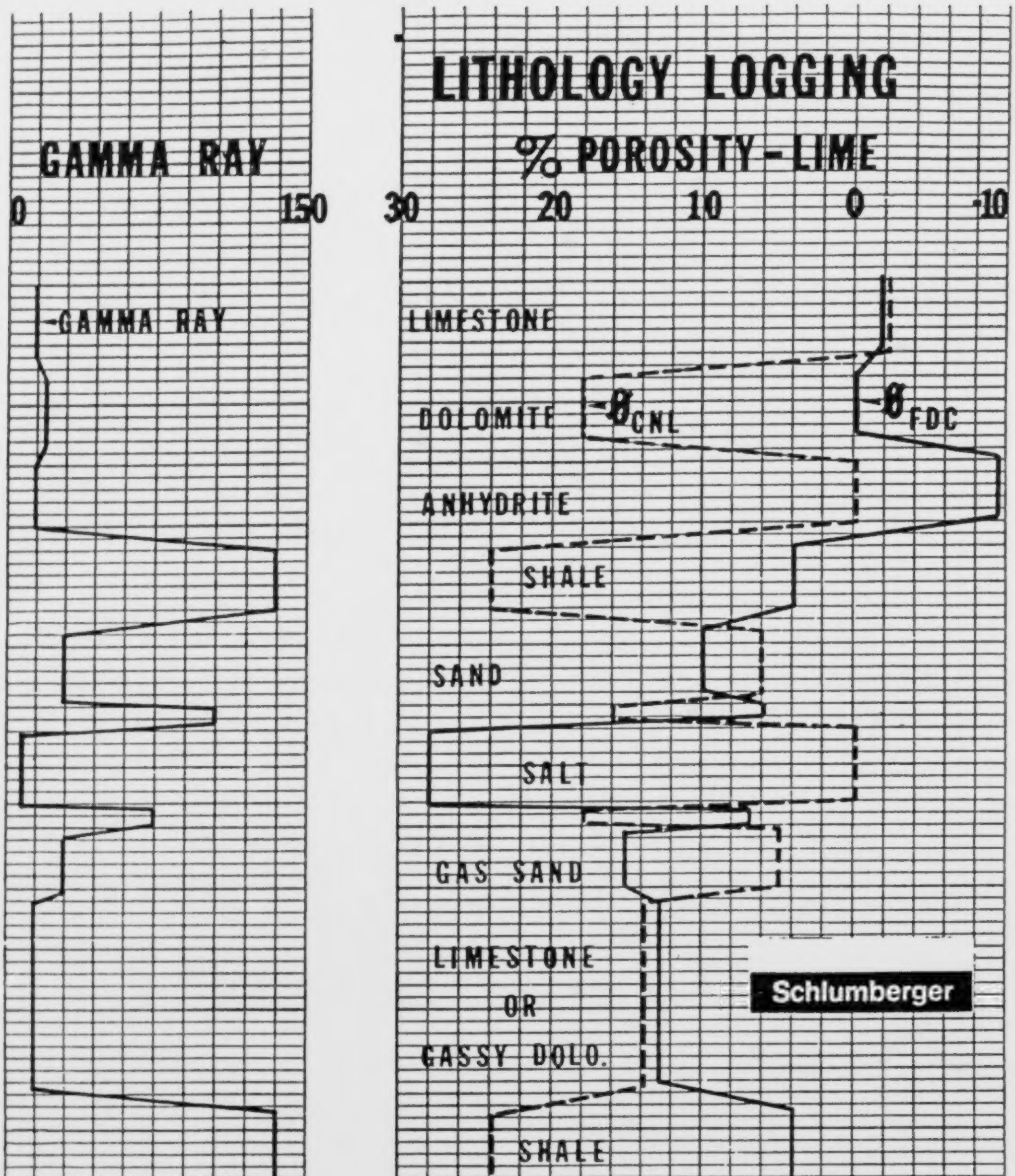


Figure 6. Example of generalized lithology logging with combination Gamma Ray Neutron-Density Log. Figure shows the sample relationships between log responses and the rock type used as a tool for determining lithology of the Charlie Lake strata (modified after Asquith and Gibson, 1982).

2.0.0 REGIONAL STRATIGRAPHY

The Triassic strata of the Western Canada Sedimentary Basin forms a southwestward-thickening wedge of sediment. The wedge is thickest in the western most outcrops of the Rocky Mountain Foothills were the strata is up to 1200m thick (Figure 7). The strata thins eastward to an erosional edge. The Triassic strata unconformably overlie Permian rocks of the Fantasque Formation in the outcrop belt and the Belloy Formation in the subsurface. Triassic rocks are unconformably overlain by marine shales of the Jurassic Fernie Formation except in some parts of northeastern British Columbia were the succession is unconformably overlain by Lower Cretaceous strata of the Gething or Bluesky Formations (Figure 8). In the subsurface, the Triassic strata blankets 142,000 square km of northeastern British Columbia and west-central Alberta (Willis, 1992). The Triassic succession contains faunas ranging in age from Early Triassic (Griesbachian) to Late Triassic (Norian). This spans a period of noncontinuous deposition of approximately 37 million years.

In the Peace River subsurface, the Charlie Lake Formation belongs to the Schooler Creek Group and is overlain by the Baldonnel Formation and underlain by the Halfway Formation also of the Schooler Creek Group. In the outcrop belt of the Williston Lake area, the Halfway Formation is replaced by the Liard Formation. To the west, the Charlie Lake Formation grades into the Ludington Formation. Since the Charlie Lake Formation is the strata of concern, only it and the related formations above (Baldonnel) and below (Halfway) will be further discussed. The Triassic nomenclatural systems for the two study areas are given in Figures 8 and 9.

2.1.0 Halfway Formation

In a Triassic study of the subsurface in the Peace River area, the Halfway Formation was first defined by Hunt and Ratcliffe (1959) as a marine sandstone overlying the Toad-Grayling Formations. Hunt and Ratcliffe (1959) state the Halfway / Toad contact as disconformable in the Peace River area, but to the west the contact becomes conformable and transitional. The upper contact of the Halfway Formation is conformable in the east and to the west, but it is also transitional in the west with the Charlie Lake Formation.

In the eastern part of the subsurface Peace River area, the Halfway Formation is overlain by redbeds and evaporites of the Charlie Lake Formation, but in the west it is overlain by marine sandstone facies of the Charlie Lake Formation (Hunt and Ratcliffe, 1959). The contact in the west with the overlying marine sandstone is not well defined lithologically. Hunt and Ratcliffe (1959) interpret the Halfway Formation to be a basal sand deposit lithologically similar to the overlying sandstone facies of the Charlie Lake Formation, but

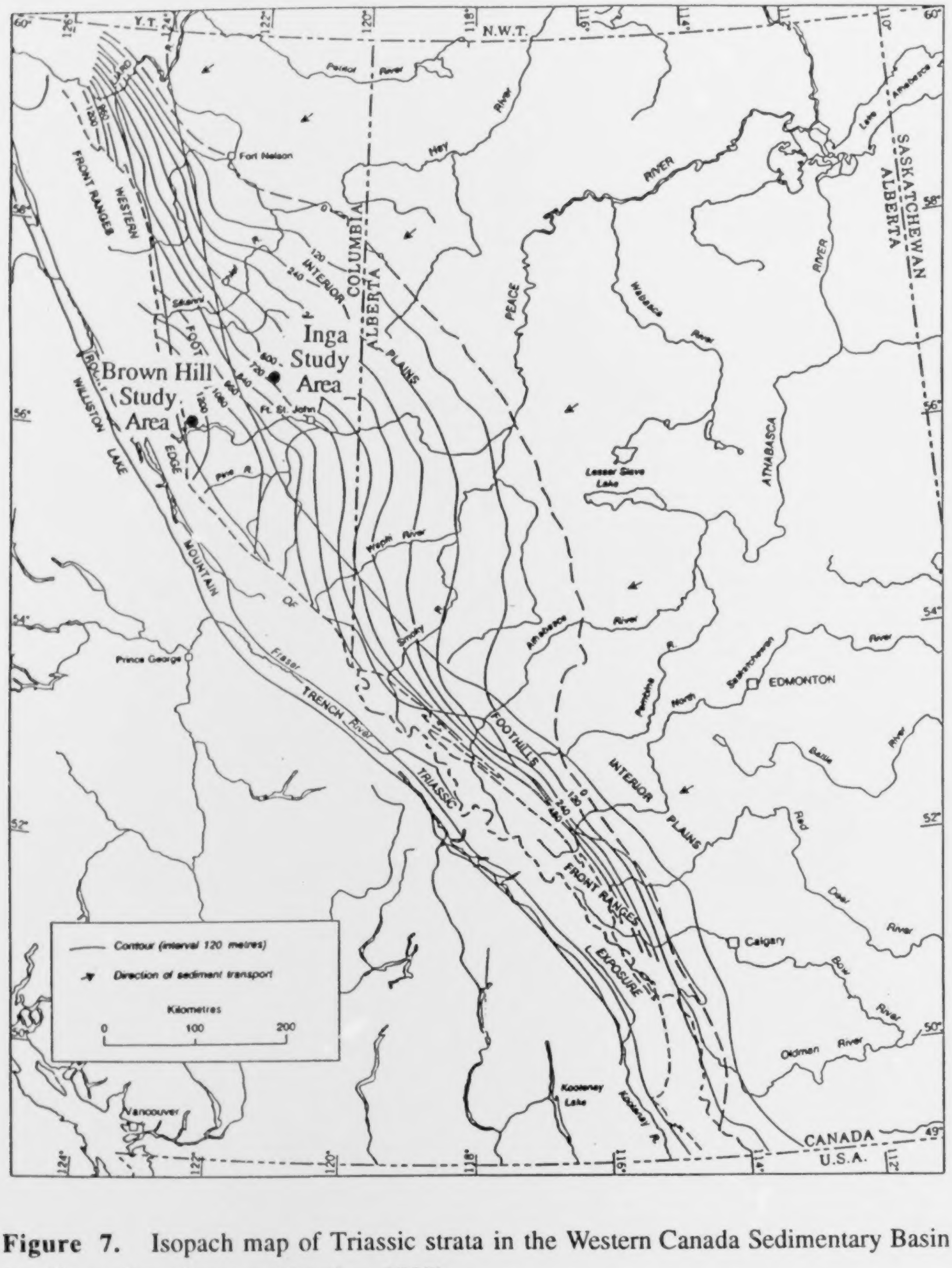

Y.T.
N.W.T.
60°
58°
56°
54°
52°
50°
49°
126°
124°
122°
120°
118°
116°
114°
112°
110°
Fort Nelson
Hay
River
Petitot River
RIVER
PEACE
SASKATCHEWAN
ALBERTA
COLUMBIA
ALBERTA
Athabasca
Lake
ATHABASCA
RIVER
Wabasca
River
Lesser Slave Lake
FRONT RANGES
WESTERN
INTERIOR
PLAINS
FOOT
Inga Study Area
Brown Hill Study Area
Ft. St. John
WILLISTON LAKE
EDGE
Pine R.
Wapiti River
MOUNTAIN
OF
Smoky R.
Athabasca River
Pembina R.
North Saskatchewan
River
EDMONTON
Prince George
Fraser
TRENCH
River
TRIASSIC
FOOTHILLS
INTERIOR
PLAINS
FRONT RANGES
EXPOSURE
Red Deer River
Battle River
Calgary
Bow River
Oldman River
Kootenay Lake
Kootenay R.
Vancouver
CANADA
U.S.A.
0
120
240
600
720
840
960
1080
1200
Contour (interval 120 metres)
Direction of sediment transport
Kilometres
0
100
200

Figure 7. Isopach map of Triassic strata in the Western Canada Sedimentary Basin (modified after Gibson and Barclay, 1989).

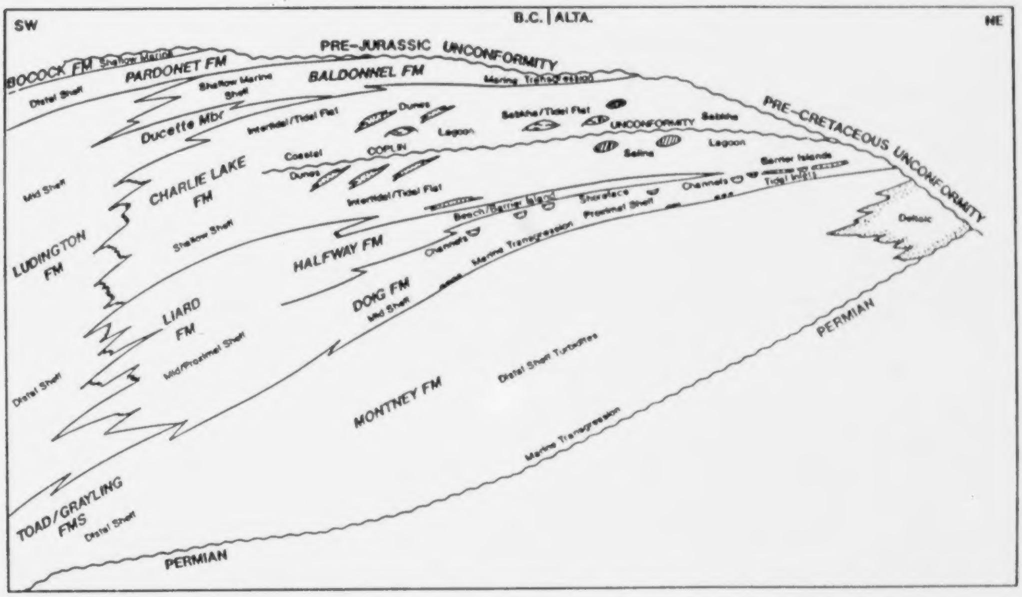

SW
B.C.
ALTA.
NE
PRE-JURASSIC UNCONFORMITY
BOCOCK FM
Shallow Marine
PARDONET FM
Distal Shelf
Shallow Marine Shelf
BALDONNEL FM
Marine Transgression
Ducette Mbr
Intertidal/Tidal Flat
Dunes
Lagoon
Sabkha/Tidal Flat
UNCONFORMITY
Sabkha
PRE-CRETACEOUS UNCONFORMITY
Coastal
COPLIN
Salina
Lagoon
Dunes
Barrier Islands
Tidal Inlets
Mid Shelf
CHARLIE LAKE FM
Intertidal/Tidal Flat
Beach/Barrier Island
Shoreface
Channels
Proximal Shelf
Deltaic
Shallow Shelf
LUDINGTON FM
HALFWAY FM
Channels
Marine Transgression
LIARD FM
DOIG FM
Mid Shelf
PERMIAN
Mid/Proximal Shelf
Distal Shelf
Distal Shelf Turbidites
MONTNEY FM
Marine Transgression
TOAD/GRAYLING FMS
Distal Shelf
PERMIAN

Figure 8. Schematic cross-section showing the relationships and depositional environments of Triassic formations between the subsurface Peace River area (NE) and the foothills (SW) (modified after Gibson and Edwards, 1990).

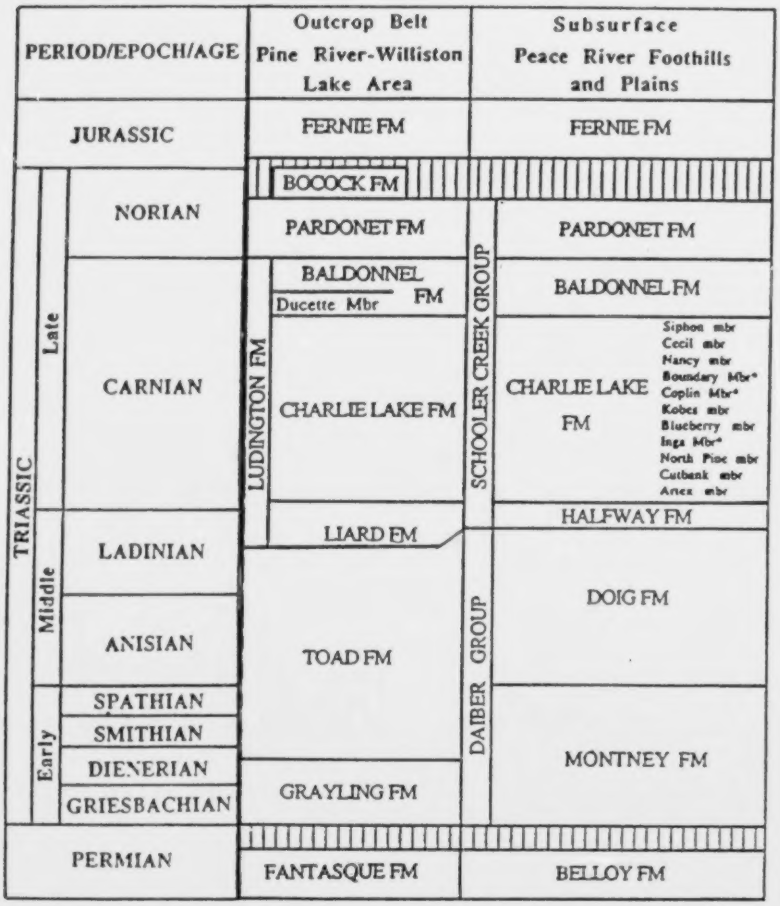

PERIOD/EPOCH/AGE
Outcrop Belt
Pine River-Williston
Lake Area
Subsurface
Peace River Foothills
and Plains
JURASSIC
FERNIE FM
FERNIE FM
TRIASSIC
Late
Middle
Early
NORIAN
CARNIAN
LADINIAN
ANISIAN
SPATHIAN
SMITHIAN
DIENERIAN
GRIESBACHIAN
BOCOCK FM
PARDONET FM
LUDINGTON FM
BALDONNEL FM
Ducette Mbr
CHARLIE LAKE FM
LIARD FM
TOAD FM
GRAYLING FM
SCHOOLER CREEK GROUP
PARDONET FM
BALDONNEL FM
CHARLIE LAKE FM
Siphon mbr
Cecil mbr
Nancy mbr
Boundary Mbr*
Coplin Mbr*
Kobes mbr
Blueberry mbr
Inga Mbr*
North Pine mbr
Cutbank mbr
Artex mbr
HALFWAY FM
DAIBER GROUP
DOIG FM
MONTNEY FM
PERMIAN
FANTASQUE FM
BELLOY FM

Figure 9. Stratigraphic nomenclature of the Triassic system in northern Alberta and British Columbia. The members of the Charlie Lake Formation are informal, except where starred, and designated after oil producing horizons (modified after Gibson and Edwards, 1990).

extending a farther distance east.

McLearn's (1940) lithologic "Grey Beds" unit, exposed in the Halfway and Sikanni Chief valleys, is divided into four zonal units (Figure 10). These are in ascending order; the upper part of the *Nathorstites* fauna, the *Lingula selwyni* fauna, the Mahaffy Cliff fauna, and the *Lima poyana* fauna (Hunt and Ratcliffe, 1959). *Lingula selwyni* has been found in cores from the Halfway Formation making it at least Carnian in age and correlatable to the base of the Grey Beds. The presence of the upper part of the *Nathorstites* fauna in some of the cores also makes the Halfway Formation correlative with the upper part of the Liard Formation.

The erosive nature of the basal contact of the Halfway Formation was originally interpreted as representing a marine transgression over the underlying shales (Hunt and Ratcliffe, 1959; Armitage, 1962). Recent detailed sedimentologic studies have interpreted the Halfway Formation as a regressive shoreface sequence with several scouring tidal inlet sequences (Campbell and Horne, 1986; Cant, 1986; Munroe and Moslow, 1990). The shales beneath the shoreface sandstone are also placed within the Halfway Formation representing the offshore component of the regressive system.

With the advent of sequence stratigraphy, at least five upward-coarsening cycles or parasequences have been identified in the Middle Triassic interval (Willis, 1992). Each cycle represents the progradation of a barrier island complex to the southwest. The shales of the Doig Formation represent offshore shelf deposition and the sandy Halfway Formation represents the adjacent shoreface deposits. The redbeds and evaporites of the overlying Charlie Lake Formation represent the backbarrier deposits of each progradational cycle. This indicates that the Doig, Halfway and Charlie Lake Formations are time-equivalent units and are conformable with each other.

2.2.0 Charlie Lake Formation

The Charlie Lake Formation stratigraphically overlies the Halfway Formation (Figure 9). The contact with the Halfway Formation is conformable (Armitage, 1962; Barclay and Leckie, 1986; Cant, 1986; Campbell and Horne, 1986; Gibson and Edwards, 1990) and represents a transition from shoreline deposits to coastal plain deposits. Campbell et al (1989) however, interpreted an unconformity at the Charlie Lake / Halfway contact with the Charlie Lake Formation resting on the Doig Formation to the east. No evidence of this regional unconformity has yet been found from outcrop descriptions and studies (Gibson and Edwards, 1990). The Charlie Lake Formation is overlain stratigraphically by the Baldonnel Formation (Figure 9). The contact is conformable, and in the subsurface is also

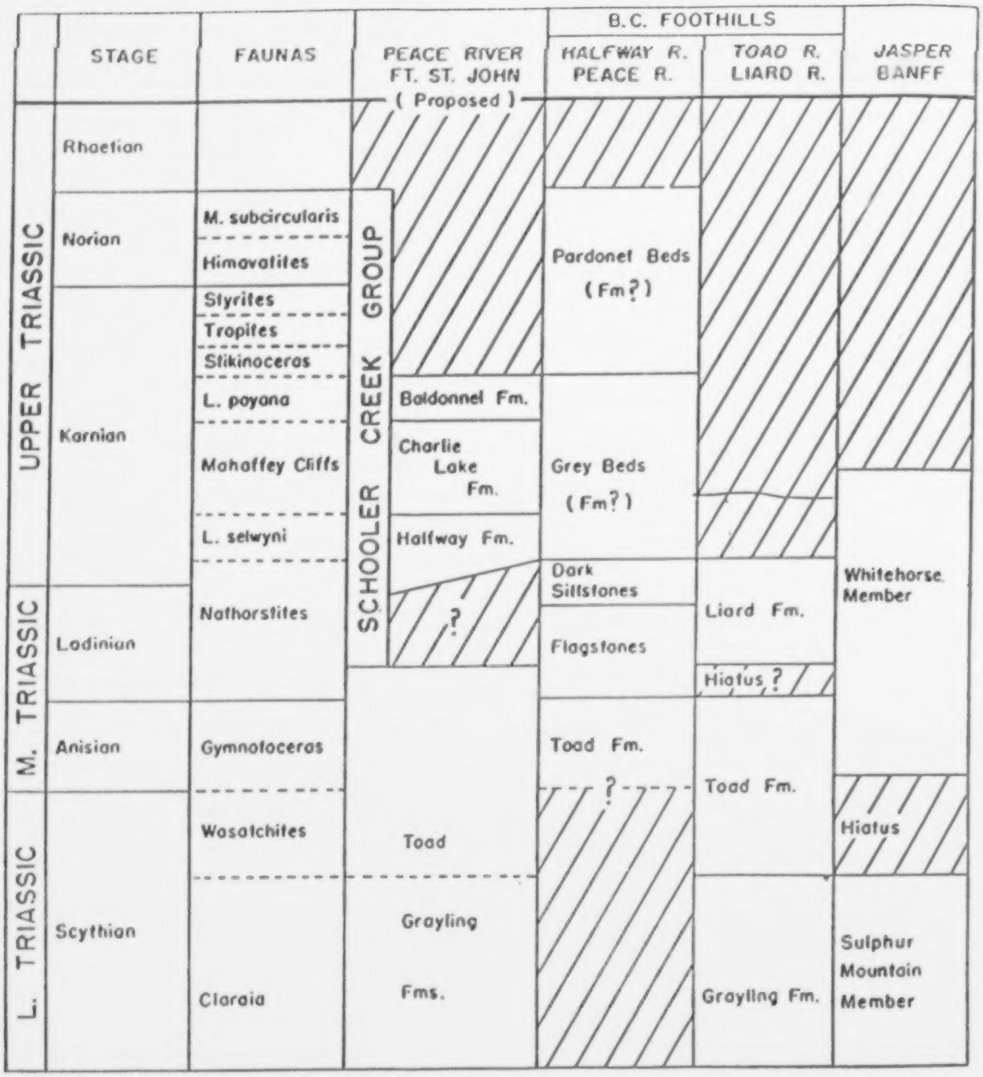

STAGE
FAUNAS
PEACE RIVER FT. ST. JOHN
(Proposed)
B.C. FOOTHILLS
HALFWAY R. PEACE R.
TOAD R. LIARD R.
JASPER BANFF
UPPER TRIASSIC
M. TRIASSIC
L. TRIASSIC
Rhaetian
Norian
Karnian
Ladinian
Anisian
Scythian
M. subcircularis
Himavatites
Styrites
Tropites
Stikinoceras
L. poyana
Mahaffey Cliffs
L. selwyni
Nathorstites
Gymnotoceras
Wasatchites
Claraia
SCHOOLER CREEK GROUP
Baldonnel Fm.
Charlie Lake Fm.
Halfway Fm.
?
Toad
Grayling
Fms.
Pardonet Beds
(Fm?)
Grey Beds
(Fm?)
Dark Siltstones
Flagstones
Toad Fm.
?
Liard Fm.
Hiatus ?
Toad Fm.
Grayling Fm.
Whitehorse Member
Hiatus
Sulphur Mountain Member

Figure 10. Stratigraphic nomenclature of the Triassic in the Peace River area and associated faunal zones (modified after Hunt and Ratcliffe, 1959).

gradational to the point that it is difficult to assign in some areas. In this study, the lithologic contacts for the Charlie Lake Formation are placed at the base of the first anhydrite and the top of the last anhydrite.

Fauna that are normally used for biostratigraphy are absent from the Charlie Lake Formation probably due to the arid environment of deposition. Age of the formation is thus based on the ages of surrounding formations. The *Lima poyana* fauna of the upper Grey Beds have been identified in the overlying Baldonnel Formation making it Upper Carnian in age (Figure 10). The lower faunal zone of the Grey Beds (*Lingula selwyni*) have been correlated with the underlying Halfway Formation making it Early Carnian in age. This deduction (Hunt and Ratcliffe, 1959) infers that the Charlie Lake Formation is equivalent to the Mahaffy Cliffs faunal zone of the Grey Beds (Figure 10). As well, the reddish nature of the Mahaffy Cliff beds are lithologically similar to the reddish nature of the Charlie Lake Formation strata. The Ludington Formation to the west of the study areas is the western facies equivalent of the Liard, Charlie Lake and Baldonnel Formations (Figure 8). The Ludington Formation section correlative to the Charlie Lake Formation contains ammonoids, bivalves and conodonts of Late Triassic Carnian age.

The subsurface Charlie Lake Formation contains three formally defined members and up to 14 informal members used by petroleum companies to represent marker units and oil and gas reservoirs. The formal members in ascending order are the Inga, the Coplin and the Boundary. The informal members used for correlations in this study, in ascending order, are the Artex, the North Pine (A and B), the Farrell, the Blueberry, the Kobes, the Nancy and the Cecil. As well, two distinct marker beds are used for correlations and are referred to as the lower Charlie Lake marker and the upper Charlie Lake marker. The Artex, North Pine A and B, Inga, Farrell, Blueberry and Cecil are dominantly sandstones and are interpreted as aeolian dune deposits (Gibson and Edwards, 1990). The Kobes, Coplin, Boundary and Nancy are dominantly dolostone and anhydrite.

The subsurface strata of the Charlie Lake Formation contains one local and two regional unconformities of stratigraphic significance. The regional Coplin unconformity occurs throughout most of northeastern British Columbia and can be traced into western Alberta. The unconformity is stratigraphically situated below the anhydrite of the Coplin Member. This unconformity truncates the Charlie Lake members (formal and informal), the Halfway, Doig and Montney Formations below it from the southwest to the northeast. The Coplin unconformity is significant because of its regional extent and its proximity to the Inga Member. The regional Boundary unconformity is stratigraphically situated above the Boundary Member and merges eastward into the Coplin unconformity (Gibson and

Edwards, 1990). The local unconformity is the Siphon disconformity which does not affect the study area as it is only present in the northeastern Peace River Arch area. None of these unconformities have been observed in Charlie Lake Formation outcrops to the west.

2.3.0 Baldonnel Formation

The Baldonnel Formation is applied to the lithologically consistent upper dolomite of the Triassic (Armitage, 1962). The formation consists dominantly of fine to microcrystalline, fossiliferous, dolomite with some residual chert and minor limestone, siltstone and shale (Hunt and Ratcliffe, 1959). In some areas (Sukunka River), the Baldonnel Formation consists of algal dolostones, calcite nodular pseudomorphs, microbreccias and dessication fractures (Barss and Montandon, 1981).

The lower contact with the underlying Charlie Lake Formation is conformable and gradational. The contact with the Charlie Lake Formation is placed at the last occurrence of evaporitic material within Charlie Lake type strata as one ascends through the Triassic strata (Hunt and Ratcliffe, 1959). The anhydrite marker grades vertically into dolomite, therefore the marker illustrates progressive deepening of the Charlie Lake top. The placement of this contact can become problematic in areas where the Baldonnel Formation contains microbreccias, calcite nodular pseudomorphs and anhydrites. However the occurrence of these evaporites within the distinctive upper dolomite of the Triassic aids in defining the contact.

The age of the Baldonnel Formation is based on the identification of *Lima poyana* from cores in the Blueberry, Buick Creek, Fort St. John and Pouce Coupe areas (Hunt and Ratcliffe, 1959). The *Lima poyana* fauna is found at the top of McLearn's (1940) 'Grey Beds" of Triassic outcrop exposures, making the Baldonnel Upper Carnian in age (Figure 10). The correlation is further aided by the lithologic similarity of the upper "Grey Beds" to the Baldonnel Formation.

The Baldonnel Formation represents the beginning of another transgressive-regressive phase showing a series of shallowing upward sequences within an overall transgressive sequence (Gibson and Edwards, 1990). A typical cycle is characterized by very shallow water subtidal mudstones and wackestones overlain by shallow subtidal to lower intertidal packstone and grainstone capped by intertidal and supratidal algal mats, red beds and anhydrite (Barss and Montandon, 1981).

2.4.0 Discussion of Regional Stratigraphy

Triassic strata of the Western Canada Sedimentary Basin can be subdivided into three regional transgressive-regressive marine assemblages (Gibson and Barclay, 1990) with several minor cycles within each assemblage (Barss and Montandon, 1981; Aukes and Webb, 1986; Wittenberg, 1992; Willis, 1992). Strata of the Doig, Halfway, and Charlie Lake Formations form the middle assemblage, while strata of the Baldonnel and Pardonet Formations form the upper assemblage (Figure 11). These assemblages are synchronous with other North American transgressive-regressive cycles (Embry, 1988).

The presence of these cycles within the assemblages and the concept of sequence stratigraphy aids in solving many of the stratigraphic problems of the Triassic strata in the Western Canada Sedimentary Basin. Many of these problems are due to the lack of biostratigraphic control in the subsurface and the use of lithostratigraphy. Interpretations using lithostratigraphic correlations often overlook the probability that these lithologically similar units are diachronous. The controversy of formational contacts, pinching out of rock units, and unconformities used in lithostratigraphic correlations can now be explained by the use of parasequences of the sequence stratigraphic concept. However, more biostratigraphy is needed to truly define the depositional history of the Triassic strata within the basin.

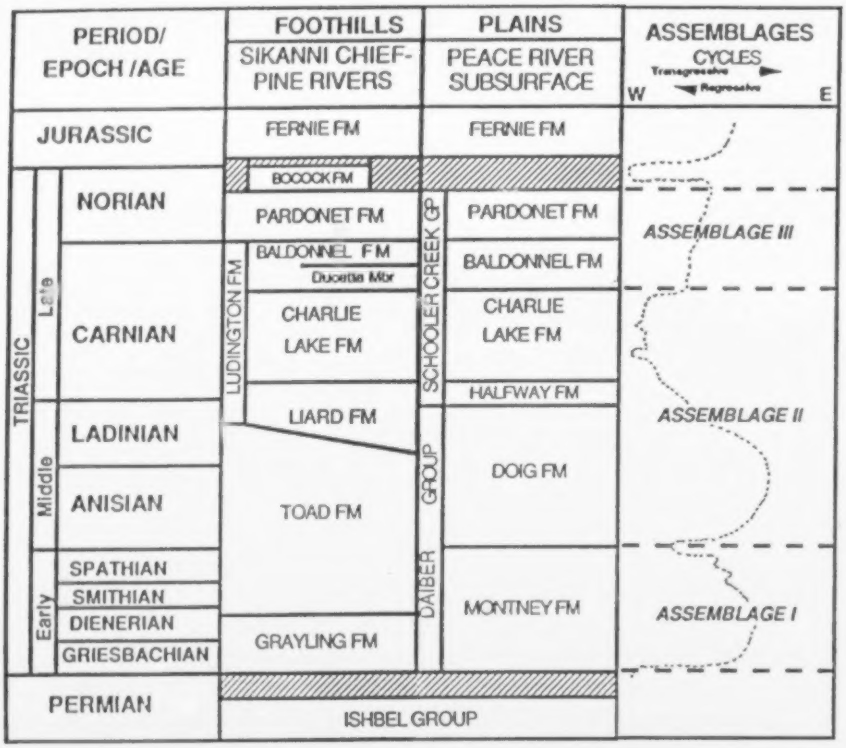

PERIOD/ EPOCH /AGE
FOOTHILLS
SIKANNI CHIEF-PINE RIVERS
PLAINS
PEACE RIVER SUBSURFACE
ASSEMBLAGES
CYCLES
Transgressive
Regressive
W
E
JURASSIC
FERNIE FM
FERNIE FM
TRIASSIC
Late
Middle
Early
NORIAN
CARNIAN
LADINIAN
ANISIAN
SPATHIAN
SMITHIAN
DIENERIAN
GRIESBACHIAN
BOCOCK FM
PARDONET FM
BALDONNEL FM
Ducette Mbr
CHARLIE LAKE FM
LIARD FM
TOAD FM
GRAYLING FM
LUDINGTON FM
SCHOOLER CREEK GP
DAIBER GROUP
PARDONET FM
BALDONNEL FM
CHARLIE LAKE FM
HALFWAY FM
DOIG FM
MONTNEY FM
ASSEMBLAGE III
ASSEMBLAGE II
ASSEMBLAGE I
PERMIAN
ISHBEL GROUP

Figure 11. Stratigraphic nomenclature and correlation of Triassic formations, members and transgressive-regressive cycles of the Western Canada Sedimentary Basin (modified after Gibson and Barclay, 1989).

3.0.0 DEPOSITIONAL SETTING

Triassic strata of the Western Canada Sedimentary Basin accumulated along the western margin of the North American craton with sediment deposition into the proto-Pacific ocean (Figure 12) or Panthalassa Sea (Tozer, 1982). The sedimentary section is preserved as a northwest to southeast belt of sediment from the Yukon to Southern Alberta (Figure 7). Local subsidence along the continental margin may have produced embayments such as the Peace River Arch Embayment (Barclay et al., 1990). It is believed by some researchers (Gibson and Barclay, 1989) that the tectonic setting was passive and analogous to the modern Atlantic continental margin while other researchers (Richards, 1989; Barclay et al., 1990) suggest that Triassic deposition occurred in an active tectonic setting during accretion of allochthonous terranes along the North American craton (Figure 13). Alternatively, if the margin was passive during Triassic deposition, it implies that the accreted terranes of Triassic age in British Columbia docked onto the North American craton as a later event and are a great distance basinward (Gibson and Edwards, 1990b).

3.1.0 Tectonic Setting

Igneous and carbonate rocks of Triassic and early Jurassic age are widespread in the western Cordillera of North America. These are interpreted as island arc volcanics and reefs which accreted to the North America craton during eastward subduction of the Panthalassan ocean (Monger et al., 1982; Tozer, 1982; Monger, 1989). Tozer (1982) suggests that there was a series of island arcs in the Panthalassan ocean some distance from the Triassic paleoshoreline (Figure 12), and that the Triassic sediments were deposited within a "miogeosyncline". There is no indication however, of how great the distance the separation was between the island arcs and the continental margin. Faunal evidence within some of the terranes suggest that they underwent northward displacement before accretion into their present location within the Cordillera (Tozer, 1982). The displacement also coincides with palaeomagnetic data (Irving et al., 1985) which places the terranes at the latitude of present day Baja California (30 degrees North) during Triassic deposition.

Other research and interpretations suggests that the active margin and exotic terranes were not so distant. The presence of bentonite clay beds within the Lower Triassic Montney Formation of the Ring-Border area of northeastern British Columbia suggests volcanic activity occurred in the area (Personal Communication, T. Moslow; 1993). Fine ash particles when blown into the atmosphere during volcanic eruptions can be transported for 100's of km's as evidenced by the Holocene ash beds in Alberta from the Mount Mazama eruption in southern Oregon. Wittenberg (1992) interpreted slump deposits of the Doig Formation as the result of seismic activity which may be the result of movements along an active margin. Evidence from underlying strata suggests that the margin was tectonically

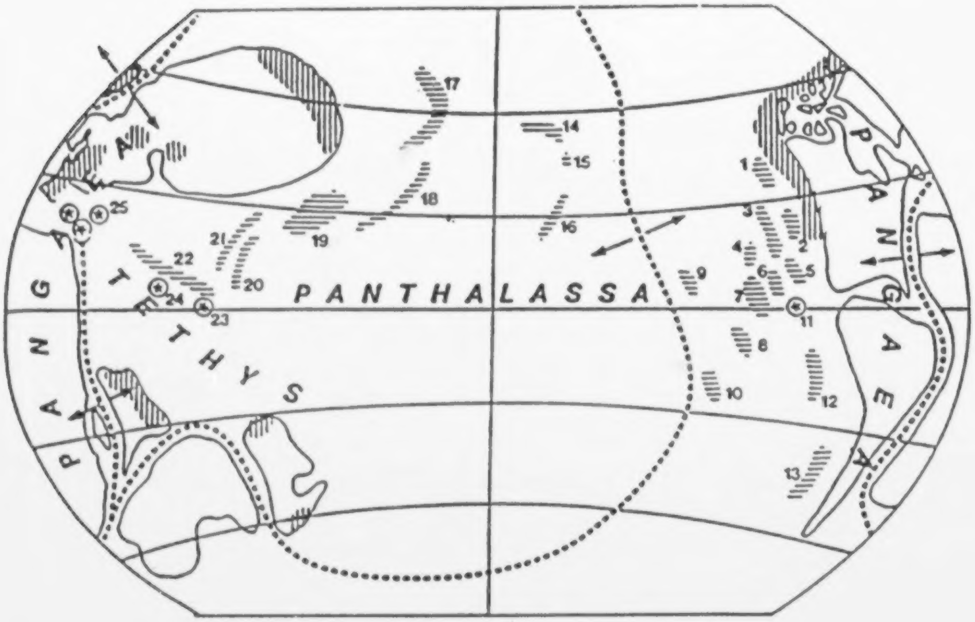

PANTHALASSA
TETHYS
PANGAEA
1
2
3
4
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Figure 12. Position of exotic terranes / island arcs off the west coast of North America during the Triassic (modified after Tozer, 1982).

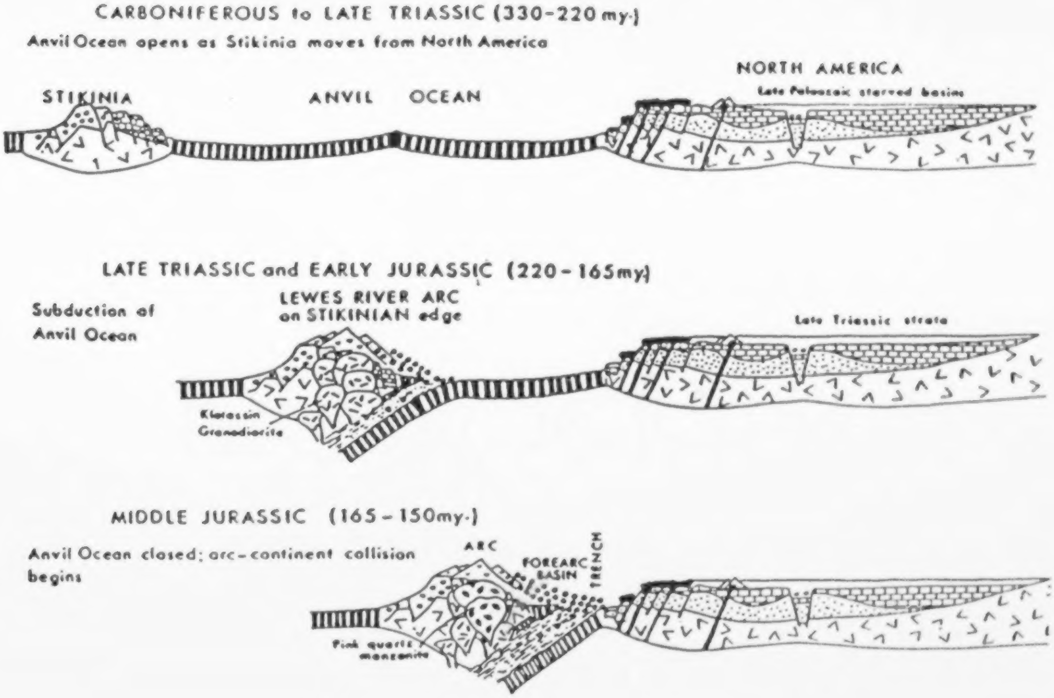

CARBONIFEROUS to LATE TRIASSIC (330-220 my.)
Anvil Ocean opens as Stikinia moves from North America
NORTH AMERICA
Late Paleozoic starved basins
STIKINIA
ANVIL OCEAN
LATE TRIASSIC and EARLY JURASSIC (220-165my.)
Subduction of Anvil Ocean
LEWES RIVER ARC on STIKINIAN edge
Late Triassic strata
Klotassin Granodiorite
MIDDLE JURASSIC (165-150my.)
Anvil Ocean closed; arc-continent collision begins
ARC
FOREARC BASIN
TRENCH
Pink quartz monzonite

Figure 13. Schematic plate tectonic reconstructions of the western margin of North America from the Carboniferous to middle Jurassic, based on data from the Yukon. The location and width of the subducting ocean floor during late Triassic time is not known (modified after Tempelman-Kluit, 1979).

active during the Carboniferous to Permian. The evidence of subduction and arc accretion during this period however, may have been displaced northward in the same fashion as the Triassic terranes (Tozer,1982).

Northwestern Alberta and northeastern British Columbia were tectonically active during the Paleozoic (Cant, 1988). During this time, the Peace River Arch had formed and the surrounding strata eventually subsided. The subsidence, along with regional tectonism, produced extensive graben systems and a broad embayment (Barclay et al., 1990). It is within this embayment that the Triassic strata of the study area was deposited.

The main graben of the area is the Fort St. John Graben (Figure 14). Smaller grabens, or satellite grabens extend off the primary Fort St. John Graben. Cant (1988) suggests the Triassic strata may have been affected by extensional faulting related to reactivation of older structures, such as faults in the Fort St. John Graben. The reactivated movement on these faults may only be a few metres, especially within the minor extensional faults, making them difficult to locate on seismic and in subsurface mapping. However, the creation of small topographic lows as a result of these minor movements may have been enough to create traps for sediment accumulation.

3.2.0 Paleoclimate and Paleolatitude

The use of paleomagnetic data places northeastern British Columbia at approximately 30 degrees N of the paleo-equator during middle Triassic time (Habicht, 1979). Sediment types which are "climate sensitive", such as carbonates, evaporites, red beds, and tillites, can be used to further verify the paleolatitude of ancient deposits. Modern carbonates (especially those containing reef-forming corals), evaporites, and red beds are dependent upon warm conditions of deposition. Most modern deposits of these types are found in arid to semi-arid regions located between the latitudes of 35 degrees N and 35 degrees S. The presence of cryptalgal laminated dolostones and limestones, evaporites, and red beds in the Charlie Lake Formation, and the laterally extensive platform carbonates of the overlying Baldonnel and Pardonet formations, suggest deposition occurred in tropical to sub-tropical latitudes within arid to semi-arid conditions.

The positioning of Triassic strata based on paleomagnetic data (Irving et al., 1985) places the study area at 30 degree N latitude. However, Campbell and Horne (1986) have inferred that Triassic winds in the Wembley field area would have been dominantly from the west. If atmospheric circulations in middle Triassic time were the same as the present day (Figure 15), the wind pattern would have westerlies (wind blowing from the west) above the 30 degree N latitude and northeasterlies below the 30 degree N latitude. Dunes

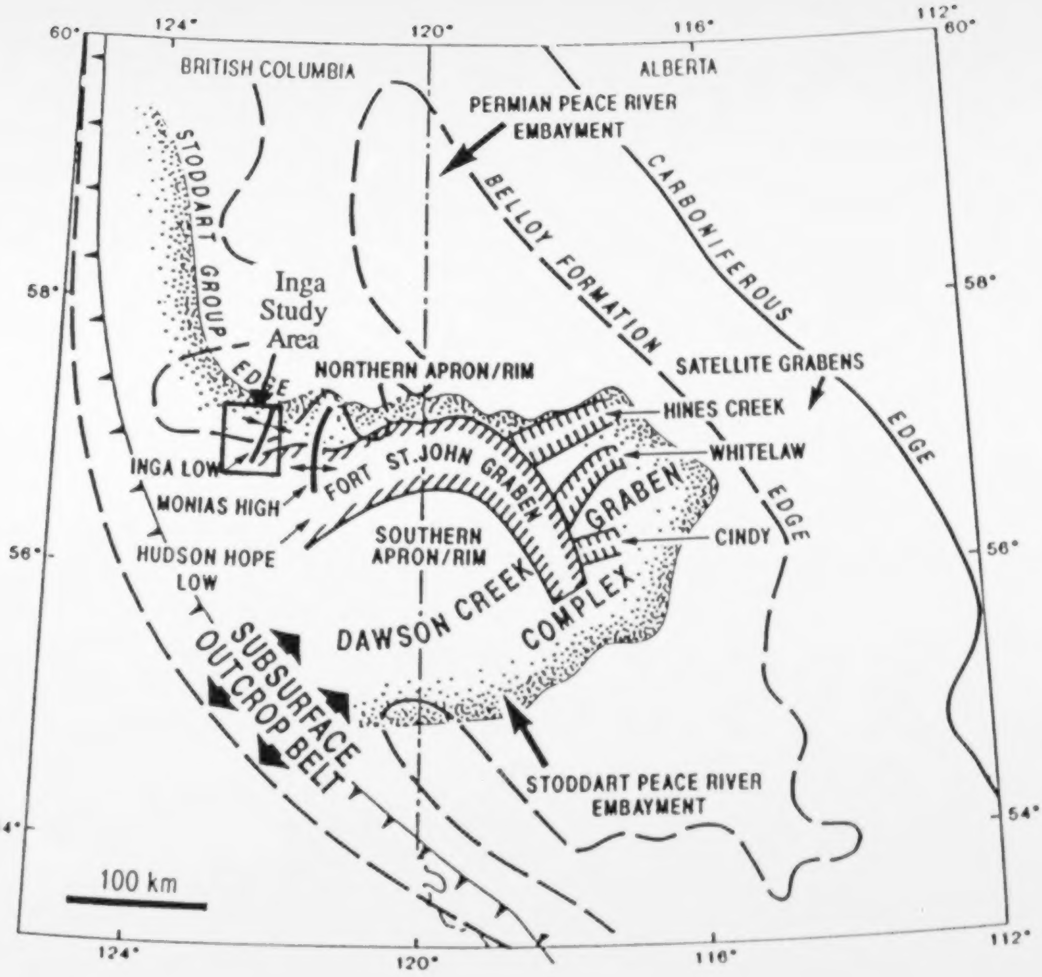

124°
120°
116°
112°
60°
58°
56°
54°
BRITISH COLUMBIA
ALBERTA
PERMIAN PEACE RIVER EMBAYMENT
CARBONIFEROUS
BELLOY FORMATION
STODDART GROUP EDGE
Inga Study Area
NORTHERN APRON/RIM
SATELLITE GRABENS
EDGE
HINES CREEK
WHITELAW
INGA LOW
MONIAS HIGH
FORT ST.JOHN GRABEN
GRABEN
EDGE
CINDY
HUDSON HOPE LOW
SOUTHERN APRON/RIM
DAWSON CREEK
COMPLEX
SUBSURFACE
OUTCROP BELT
STODDART PEACE RIVER EMBAYMENT
100 km

Figure 14. Upper Paleozoic tectonic elements of the Peace River Embayment featuring the Fort St. John graben and associated satellite grabens (modified after Barclay et al., 1990).

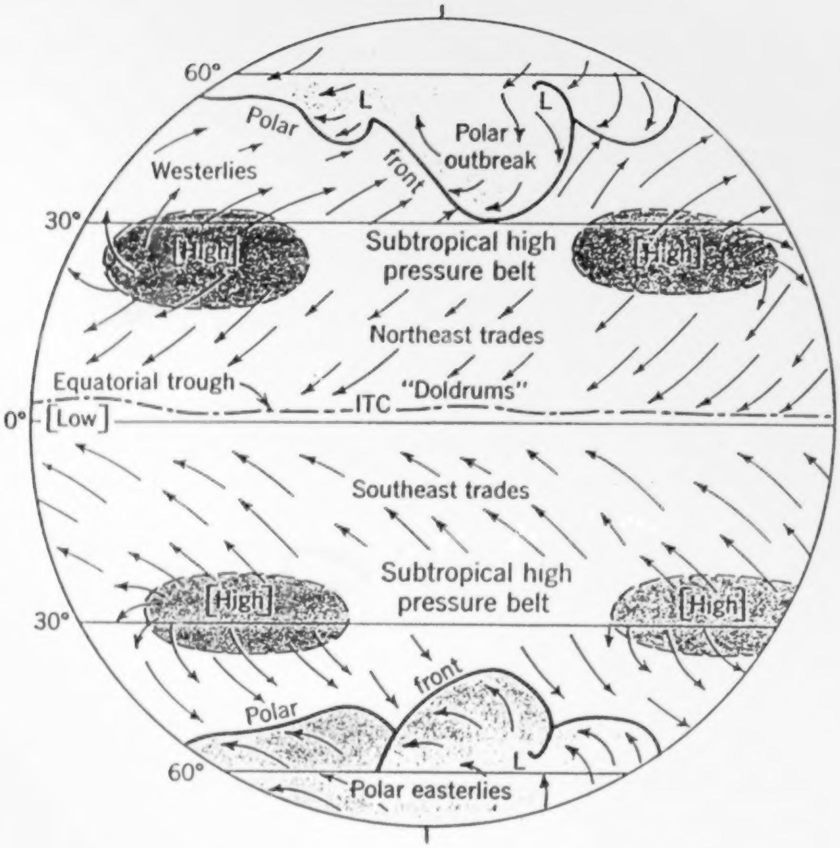

60°
L
L
Polar
Polar
outbreak
Westerlies
front
30°
High
Subtropical high
pressure belt
High
Northeast trades
Equatorial trough
ITC
"Doldrums"
0°
Low
Southeast trades
High
Subtropical high
pressure belt
High
30°
front
Polar
L
60°
Polar easterlies

Figure 15. Schematic diagram of present day global surface winds in the northern and southern hemispheres (modified after Strahler and Strahler, 1987).

in a coastal setting are subject to a wide range of wind regimes and patterns. Sand transport, however, occurs during periods of the dominant wind (Pye and Tsoar, 1990). Examination of rose diagrams (Figure 16) from dip metre logs of aeolian Charlie Lake sandstones, infers the sandstones were deposited by a dominant northeasterly wind. This wind direction suggests that the sandstones were deposited below the 30 degree N latitude (Figure 17).

3.3.0 Sediment Source

The source area of sediment for Triassic deposits including the Charlie Lake Formation is a reoccurring unsolved problem. Based on a study of measured paleocurrent transport indicators in Triassic outcrop in British Columbia (Pelletier, 1965), the dominant transport direction was generally towards the west to southwest inferring a source area to the east or northeast. This transport direction is comparable with transport directions inferred from rose diagrams of Charlie Lake Formation sandstones (Figure 16). This means that the source area for the Charlie Lake aeolian sandstones would be northeast of the study area. Permian and Pennsylvanian orthoquartzitic strata exposed east of the study area could have provided an adequate sediment source for the Charlie Lake Formation sandstones.

If the sediment source for most Triassic strata was from the northeast as hypothesised by Pelletier (1965), there had to have been some type of transport mechanism to carry the eroded sediment to the paleoshoreline of the Halfway and Charlie Lake formations. No fluvial or deltaic systems have been recognized in the deposits of the Halfway or Charlie Lake Formations. As a result, Campbell and Horne (1986) and Willis (1992) infer that the area of clastic input into the basin was from the northwest where the sediment was then transported southeast along the paleo-shoreline by longshore currents. The paleo-shoreline could also have received some sand being transported by aeolian processes. Sand held in suspension over bodies of water by strong air currents during storms, and the seaward progradation of dunes on the beach, can supply sand to shallow marine and peritidal environments. However, the limited amount of sandstone in the Charlie Lake Formation, suggests an aeolian sand supply to the Halfway shoreline would have been very volumetrically limited.

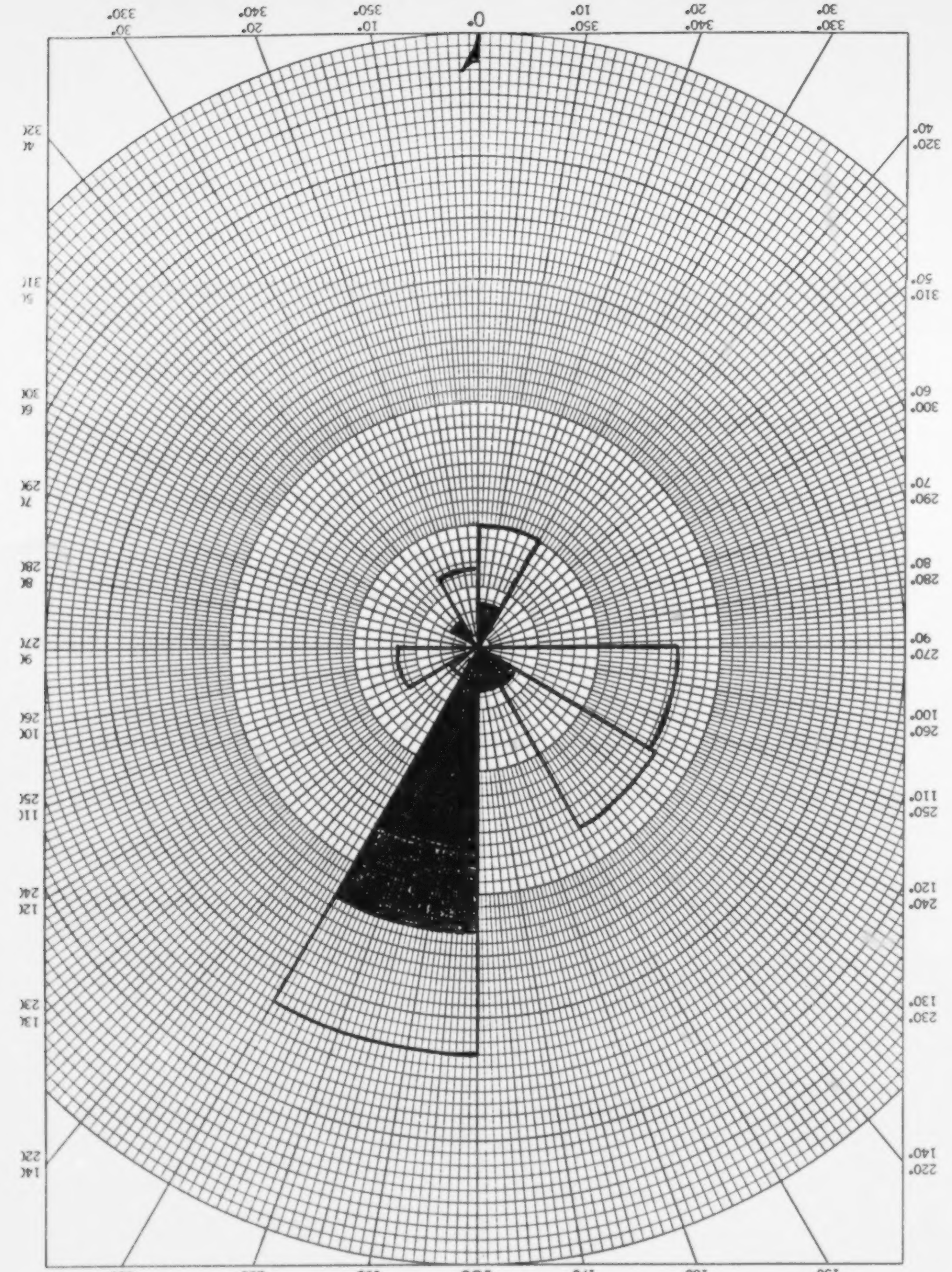


Figure 16. Rose diagram of cross-strata dip directions in the Artex Sandstone of the Charlie Lake Formation showing a prevailing dip to the southwest inferring a northeasterly wind direction.

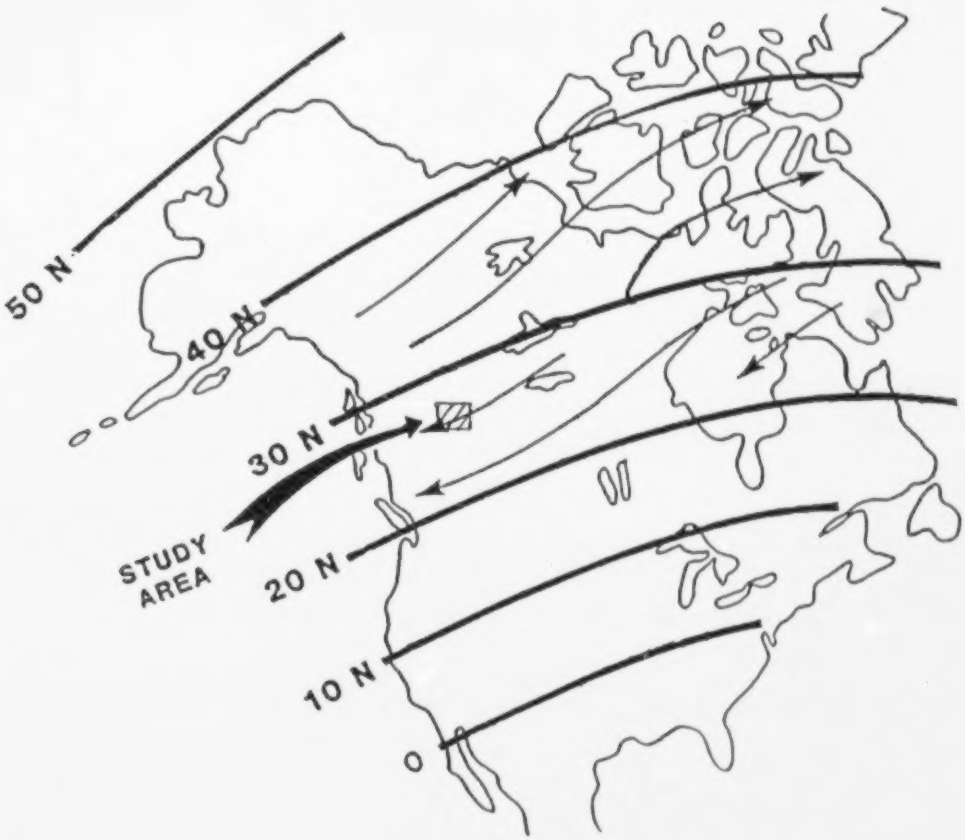

50 N
40 N
30 N
STUDY AREA
20 N
10 N
0

Figure 17. Suggested location of the Charlie Lake Formation in the surficial wind circulation patterns during Triassic time based on orientations of sandstone dip directions (modified from Campbell and Horne, 1986).

4.0.0 BROWN HILL SEDIMENTARY FACIES IN OUTCROP

There are 14 recurring lithofacies observed at the Brown Hill outcrop section in the Liard, Charlie Lake and Baldonnel Formations. The lithofacies are discussed below and summarized in Table 2.

4.1.0 Facies A. Laminated Shale

DESCRIPTION: Facies A consists of finely laminated black shale or massive mudstone (Plate 1). Laminations of silt increase in frequency upwards. The laminated shales occur in beds 5cm to 1.2m thick. Trace fossils consist of *Palaeophycus* and in some shale beds, brachiopods and carbonaceous detritus are disseminated in layers. The shales and mudstones are interbedded with sandstones of facies C, D, M and H. The shales are overlain by sandstones of facies B and C or facies H limestone with sharp planar contacts (Plate 1).

INTERPRETATION: The finely laminated shales and mudstone is a product of deposition from suspension (Harms et al., 1982). Silt laminae may have been deposited by storm events in which the normal grading upward into shale is the resumption of background pelagic deposition associated with waning of flow (Davis et al., 1989). The interbedding with hummocky cross-beds of facies B, current rippled sandstones of facies D, and subtidal mudstone limestones of facies H, along with the presence of brachiopods indicates that facies A was deposited in a marine environment mainly below mean stormweather wavebase in the offshore shelf.

4.2.0 Facies B. Horizontally Laminated Sandstone

DESCRIPTION: The sandstone is light gray, yellow, or reddish-orange, well sorted and very-fine to-fine grained. The sandstone is periodically interbedded with current rippled sandstone and mudstone layers (Facies D and A). Some beds in this facies are observed to have sub-parallel laminations that form hummocks and swales and are interpreted as hummocky cross-stratification. Individual sandstone bedsets range in thickness between 15cm to 30cm. Internal laminae are distinct, continuous, slightly wavy and thicken into the swales. Occasionally the strata display low-angle cross-stratification of 0 to 5 degrees (Plate 2). Bedsets have sharp basal contacts. The upper bedset contacts are sharp (including contacts with the sandstones and mudstones) except when they are bioturbated. Bioturbation is continuous along the contact and varies in thickness for each bedset. The upper contact of the bioturbated horizon is sharp with deposition of an overlying horizontally laminated sandstone. A few escape traces are present and truncate the horizontally laminated sandstones. Current ripples can be found on some of the bedding planes overlying the horizontally laminated sandstones. There are various deformed

Facies	Lithology	Thickness	Bedding Features	Physical Sedimentary Structures	Biogenic Sedimentary Structures	Depositional Environment
A	Laminated Shale	5cm-1.2m	Sharp Planar Contacts	Horizontally Laminated	*Palaeophycus*	Offshore Subtidal
B	Horizontally Laminated Sandstone	0.15-5m	Erosional sharp bases and gradational upper contacts Shale rip-up clasts	Hummocky cross stratification. Current Ripples. Fluid escape structures.	*Planolites* Escape Structures	Lower Shoreface (Tempestites)
C	Massive Sandstone	0.1-1m	Wavy upper and sharp lower contacts. Vugs.	None	*Palaeophycus*	Lower Shoreface
D	Rippled Laminated Sandstone	3-50cm	Sharp contacts	Asymmetrical Ripples. Massive.	*Palaeophycus* *Planolites*	Lower shoreface
E	Low-angle Planar-tabular Cross-stratified Sandstone	0.5-0.7m	Scoured bases. Fining upward.	Planar-tabular cross-beds. Asymmetrical ripples.	None	Tidal Inlet Fill
F	Sandy Laminated Carbonate Mudstone	0.3m	Flaser and lenticular bedding	Flaser, wavy, and lenticular laminations.	None	Tidal Flats (Intertidal)
G	Sandy cross-bedded Carbonate Packstone	0.1-0.2m	Scoured base. Fining upwards	Tabular-planar cross-bedding	None	Tidal channel
H	Massive Carbonate Mudstone	2-4m	Fining upwards. Vugs. Stylolites.	Massive. Brecciated Clasts.	None	Subtidal (lagoon)
I	Microbial Laminated Carbonate Mudstone	1-2m	Upper domed contacts	Fenestral fabric. Algal domes. Undulatory laminations.	None	Intertidal Flat
J	Sollution-Collapse Breccia	0.3-6m	Irregular contacts Limestone and sandstone clasts.	None.	None	Peritidal (sabkha)
K	High-angle Cross-stratified Sandstone	0.2-3m	Sharp planar contacts	Wedge-planar cross-beds. Tabular-planar Cross-beds Inverse laminations. Avalanche toes.	None	Aeolian Dune
L	Contorted Sandstone	1.5-1.8m	Gradational lower contacts with underlying high-angle cross-bedded sandstone	Inverse laminations. Parabolic folds. Disrupted laminations Contorted strata.	None	Transgressed Aeolian Dune
M	Oscillation Rippled Sandstone	0.1-5m	Wavy to sharp contacts	Symmetrical ripples. Bifurcating ripples.	None	Marine to Lacustrine (interdunal)
N	Low-angle laminated Silty Carbonate Mudstone	4-30m	Lenticular bedding. Calcite and chert lined vugs.	Low-angle, wavy laminations.	*Diplocraterion* *Teichichnus*	Subtidal (Shelf)

Table 2. Summary of sedimentary facies identified in the Brown Hill outcrop study.

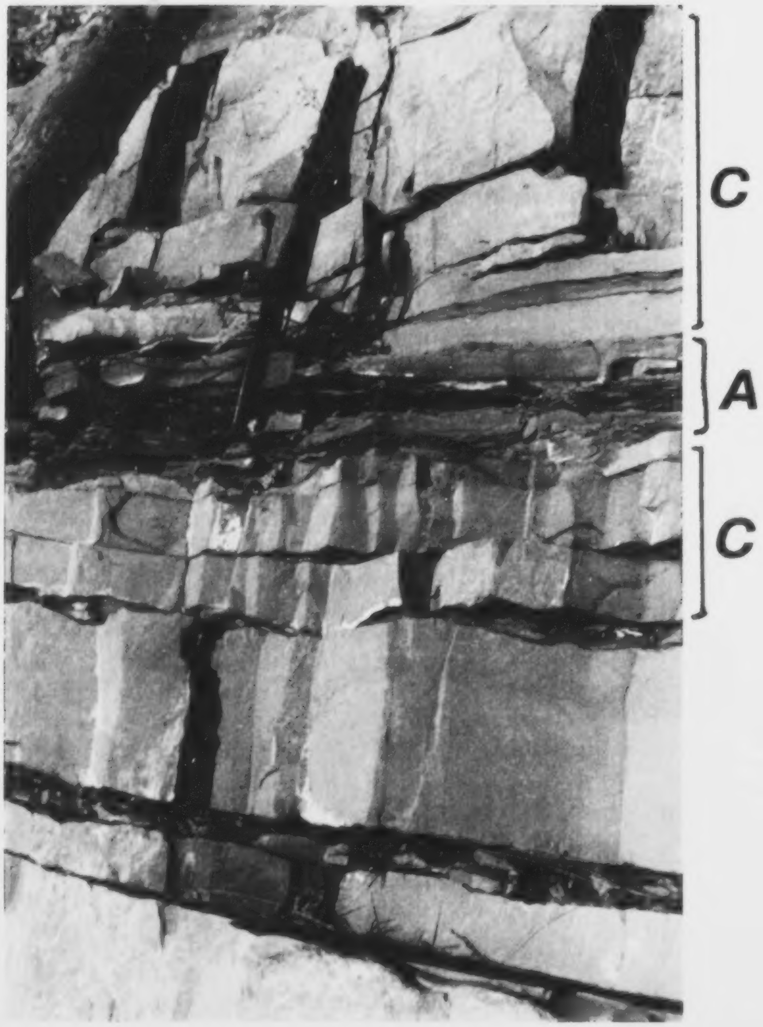


Plate 1. Interbedded laminated shale (facies A) and massive sandstone (facies C) from the Liard Formation at the Brown Hill outcrop section. Hammer for scale is 25cm long and the head is pointing up-section.

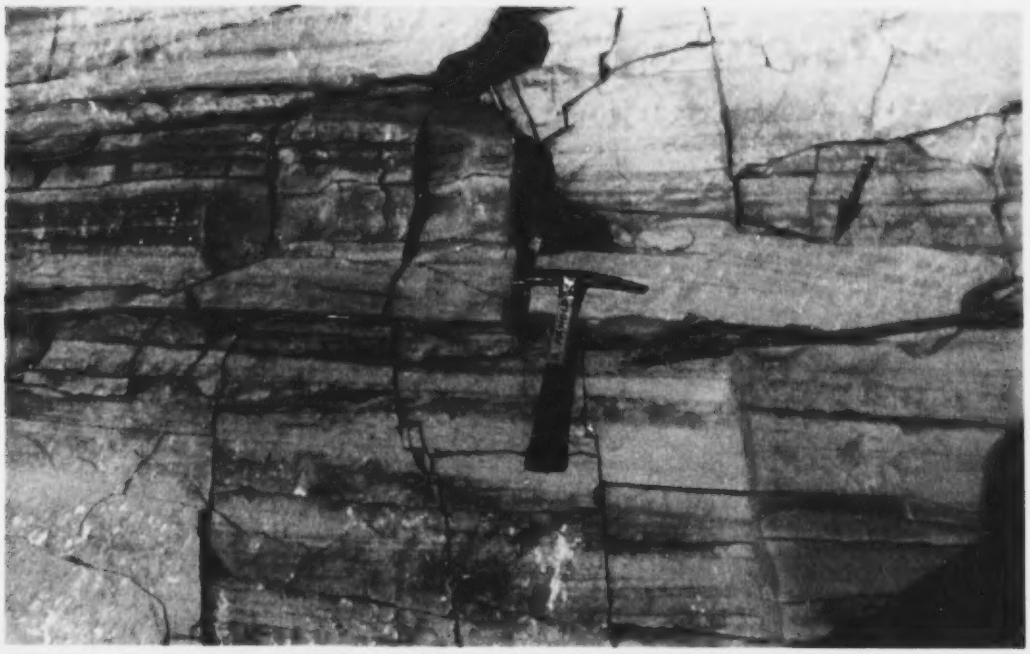


Plate 2. Horizontally laminated and hummocky cross-bedded (arrow) sandstone of facies B at the Brown Hill outcrop section. Hammer for scale is 25cm long. The hammer head points up-section.

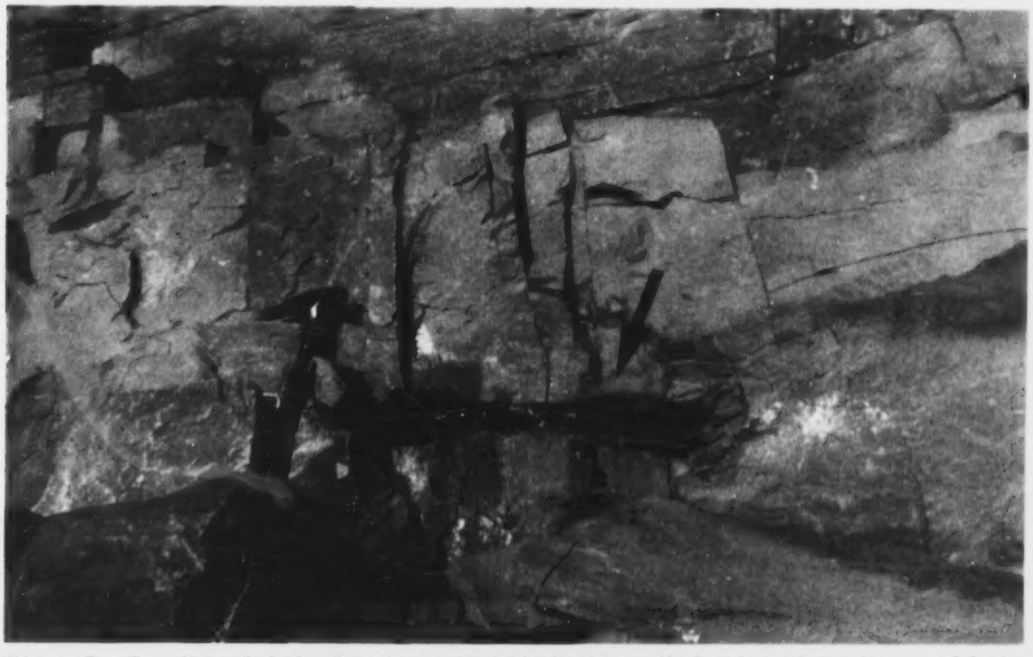


Plate 3. Laminated shale clast (arrow) within horizontally laminated sandstone of facies B. Hammer for scale is 25cm long. Hammer head points up-section.

horizons which display fluid injection structures. There are also brecciated mudstone clasts horizontally oriented (Plate 3) that occur within the horizontally laminated sandstones. The mudstone clasts vary in length between 1cm to 40cm and occur as a continueous horizon within the sandstones. Body and trace fossils are rare in the sandstone but common in the mudstone layers. Body fossils consist of brachiopods, ammonites and gastrapods. Trace fossils are horizontally dominated by forms of *Planolites*.

INTERPRETATION: The sandstone which occurs in sets typically 15cm to 30cm thick with internal laminae that are wavy, parallel or tangential to the base of the set, and thicken into the swale are interpreted as hummocky cross-stratification (Hunter and Clifton, 1982; Harms et al., 1975). Hummocky cross-stratification is believed to be formed exclusively by storm waves which can occur well below fair weather wave base (Walker, 1984). Other sedimentary features which indicate storm deposition include the sharp bases of the sandstones which occasionally have angular shale clasts. The shale clasts are interpreted as being incorperated as rip-up clasts in the sandstone due to the erosive nature of the sandstone deposition which erodes into an underlying shale bed. The deformed horizons also suggest rapid deposition and differential loading causing the pore waters of the buried sand to migrate upward to a lower pressure area forming flame and fluid escape structures (Williams, 1960). Hummocky cross-stratification and associated storm deposits are common to environments of deposition that range from upper shoreface to offshore shelf (Harms et al., 1975).

Hunter and Clifton (1982) infer a complete storm cycle to consist of a a lower hummocky cross-stratified sandstone, a middle planar and ripple-bedded sandstone, and an upper bioturbated sandstone. The storm deposit can then be overlain by post-storm/ fairweather mud representing the suspension fall-out of storm sediment or the return to normal shelf deposition (Johnstone and Baldwin, 1986). This change in flow strength from storm to normal conditions indicates an upward waning of flow (Harms et al, 1982). This cycle is frequently observed within the sandstone of facies B. The mudstone, ripple-bedded and bioturbated sandstones of the sequence however are rare due to the deep erosive nature of the following storm event which leaves amalgamated storm deposits (Figure 18) of only hummocky cross-stratified and planar sandstone (Bourgeois, 1980).

The laminated then scrambled (lam-scram) nature of parts of the sandstone enclosed between sharp bounding surfaces is characteristic of storm deposits (Ekdale et al., 1984). The laminated sandstone represents the rapid deposition of storm sands. Escape traces within the laminated sandstones also suggests rapid dep0sition. The scrambled sandstone, which is actually bioturbated sandstone, represents the return to normal quiescent

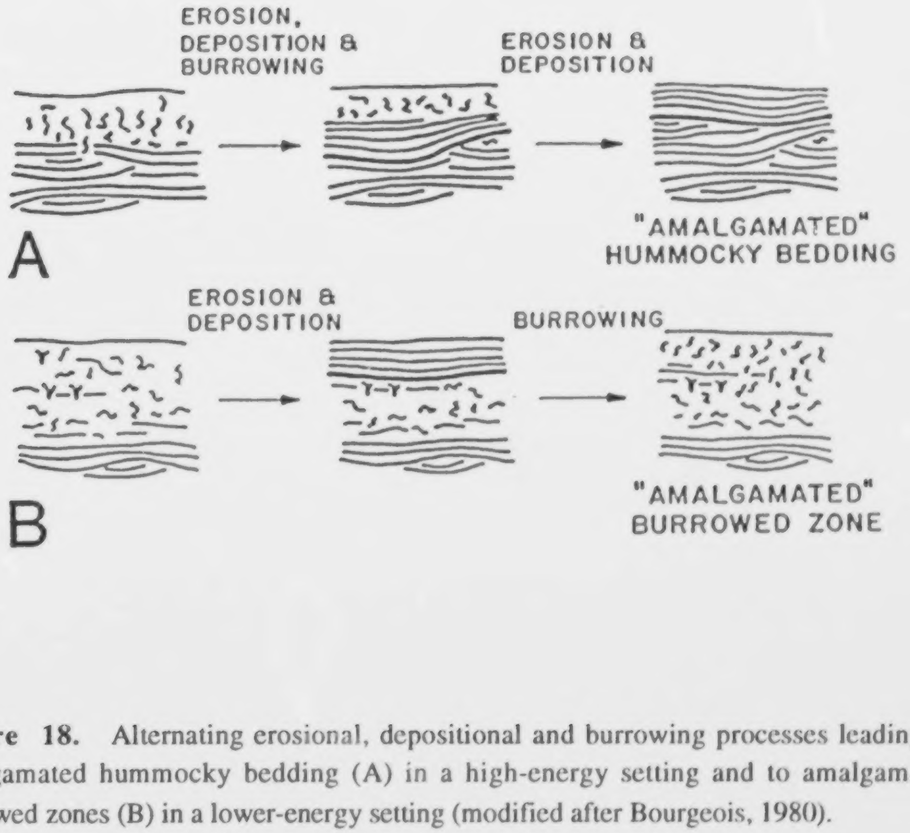

EROSION, DEPOSITION & BURROWING
EROSION & DEPOSITION
"AMALGAMATED" HUMMOCKY BEDDING
A
EROSION & DEPOSITION
BURROWING
"AMALGAMATED" BURROWED ZONE
B

Figure 18. Alternating erosional, depositional and burrowing processes leading to amalgamated hummocky bedding (A) in a high-energy setting and to amalgamated burrowed zones (B) in a lower-energy setting (modified after Bourgeois, 1980).

deposition in which organisms have time to graze through the post-storm muds and tops of storm sands before they are in turn partially removed by the next storm event (MacEachern and Pemberton, 1992).

The horizontal nature of the trace fossils and the shallow marine fauna found in the few preserved mudstones and shales also indicate a lower shoreface to offshore environment of deposition (Howard and Frey, 1990). Facies B was deposited in an offshore to lower shoreface environment of deposition within the Liard Formation.

4.3.0 Facies C. Massive Sandstone

DESCRIPTION: The massive appearing sandstone facies is yellow to reddish-orange, fine grained, and moderately sorted. Siltstone laminae usually form wispy, contorted seams within the sandstone (Plate 4). There are no other observable sedimentary structures. The sandstone is highly fractured and contains abundant vugs 1mm to 10mm in diameter. The massive sandstone facies is commonly interbedded with current-rippled sandstones (Facies D) and mudstones (Facies A). The massive sandstone occurs in beds 10cm to 1m thick and its contacts with facies A and D are undulatory to sharp. No fossils or trace fossils are observable except on bedding planes were *Palaeophycus* traces are abundant.

INTERPRETATION: The lack of sedimentary structures within the sandstone can be due to extensive bioturbation by organisms, deposition by sediment gravity flow, shocking of liquefied sediment, or by rapid deposition from suspension (Boggs, 1987). Trace fossils (*Palaeophycus*) are recognizeable but only on bedding plane surfaces. However, a mottled appearence suggestive of bioturbation is lacking. The massive sandstone is commonly overlain by beds of current rippled sandstone and laminated mudstone. This succession occurs in repetitive cycles. Some of the sandstones in these cycles are bounded by hummocky cross-bedded sandstone of facies B which are deposited by storm processes. This would infer that the massive sandstones were deposited during a possible storm event on the lower shoreface to offshore shelf. The thin silty laminae are finer grained particles that were deposited by suspension during periods of waning current flow and later deformed due to liquefaction.

4.4.0 Facies D. Ripple Lamininated Sandstone

DESCRIPTION: The ripple laminated sandstone facies consists of light brown to reddish-orange, moderately sorted sandstone. The sandstone contains a small amount (10%) of silt. The sandstone is deposited in beds 3cm to 50cm thick. The sandstones internally may be massive or display asymmetrical ripple cross-lamination (Plate 5). The sandstone beds are bioturbated in places. Identifiable trace fossils are *Planolites* and *Palaeophycus*.

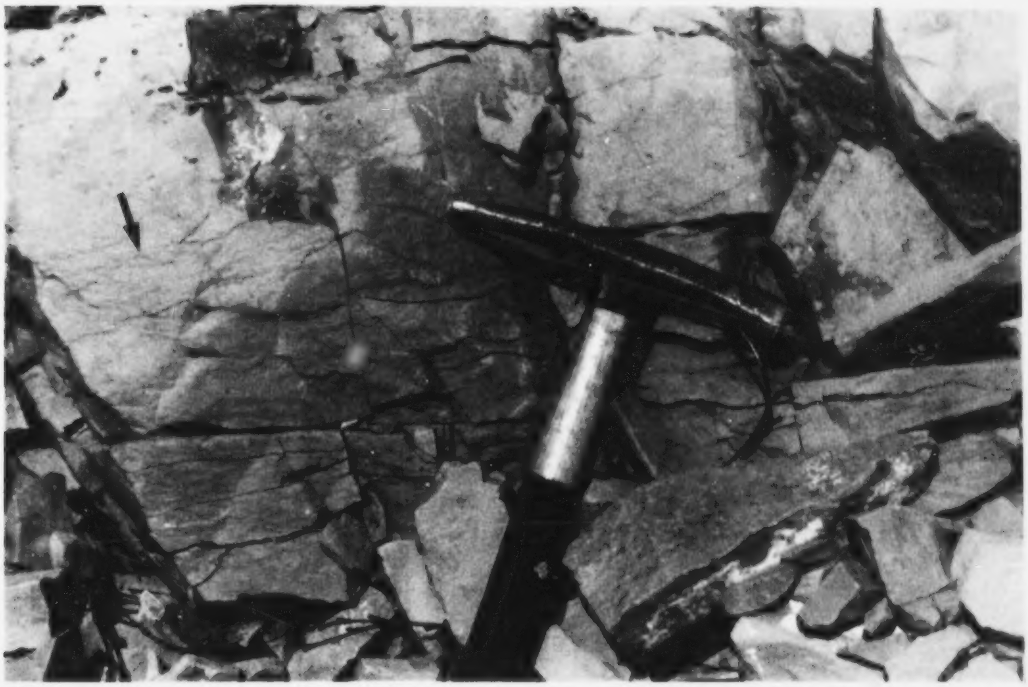


Plate 4. Wispy, contorted silt laminations (arrow) within massive appearing sandstone of facies C at the Brown Hill section. Hammer for scale is 25cm long.

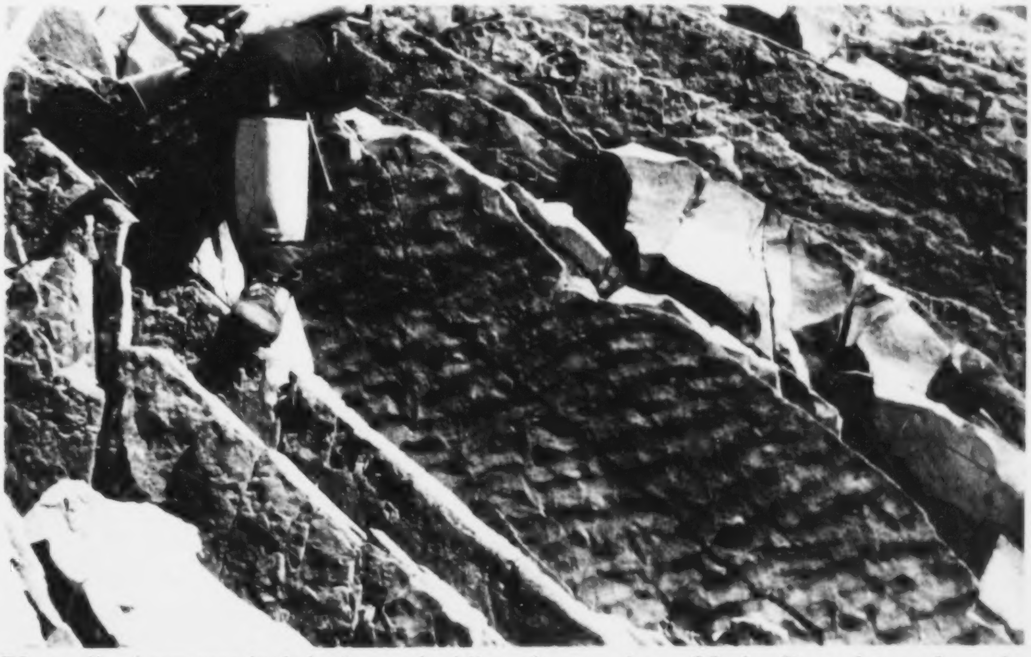


Plate 5. Asymmetrical ripples on bedding plane surface of facies D sandstone from the Liard Formation, Brown Hill section. Note leg for scale.

Facies D commonly overlies sandstones of facies B, C and E. The sandstone is overlain by laminated shale of facies A and sandstones of facies B and C. The sandstone contacts with the underlying and overlying facies are sharp.

INTERPRETATION: The cross-laminated nature of the sandstone facies, indicates deposition by currents (Harms et al., 1975) in an environment where flow strength wanes from the higher velocity current transport of sandstones of facies B, C and E to that of facies D (Hunter and Clifton, 1982). The continued waning of flow strength is culminated by the deposition of mud from suspension (facies A). The asymmetrical shape and stratigraphic positioning of the ripples suggests that once the high energy storm wave events that deposited the hummocky cross-stratified sandstones of facies B subdued, subaqueous currents transported the sands forming small scale ripples. Burrowing within the rippled sandstone also suggests a resumption of quiescent shallow marine conditions (Pemberton et al., 1992). Facies D was deposited on the lower shoreface and offshore shelf environments.

4.5.0 Facies E. Low-Angle Planar-Tabular Cross-Stratified Sandstone

DESCRIPTION: This facies consists of medium-to lower coarse-grained, light brown to buff, well sorted, sandstone. The sandstone is orthoquartzitic (98%) and is very porous. The sandstone contains fine laminations which dip 10-15 degrees (Plate 6). The planar tabular cross-beds form bedsets that are 50-70cm thick. There is a 15cm thick fine grained sandstone bed of climbing, slightly asymmetrical, ripples (facies D) at the top of one of the planar tabular, cross-stratified beds (Plate 7). There are no fossils or trace fossils identified within this facies.

INTERPRETATION: The sandstone of facies E displays normal grading from the medium grained cross-stratified sandstone beds to fine grained ripple laminated sandstone beds. The gradational change from planar-tabular cross-beds to asymmetrical ripples indicates waning current strength (Harms et al., 1982). The asymmetrical shape of the ripples and their climbing nature infers rapid sedimentation by unidirectional currents. The sedimentary structures and lack of mudstone and burrowing are indicative of a high energy environment. Such processes can be associated with a clastic shoreline (underlying rocks of facies A,B, and C), and are characteristic of tidal inlet fills (Weimer and Land, 1972; Moslow and Tye, 1985) of barrier-island tidal channels (Reinson, 1992). The lack of upper shoreface and foreshore deposits at the Brown Hill outcrop section is due to erosion caused by tidal channel migration (Hoyt and Henry, 1965). The lack of common tidal sedimentary indicators (herring-bone cross laminations, desiccation cracks) and associated trace fossils is a characteristic trend of some interpreted Triassic tidal inlet facies (Caplan,

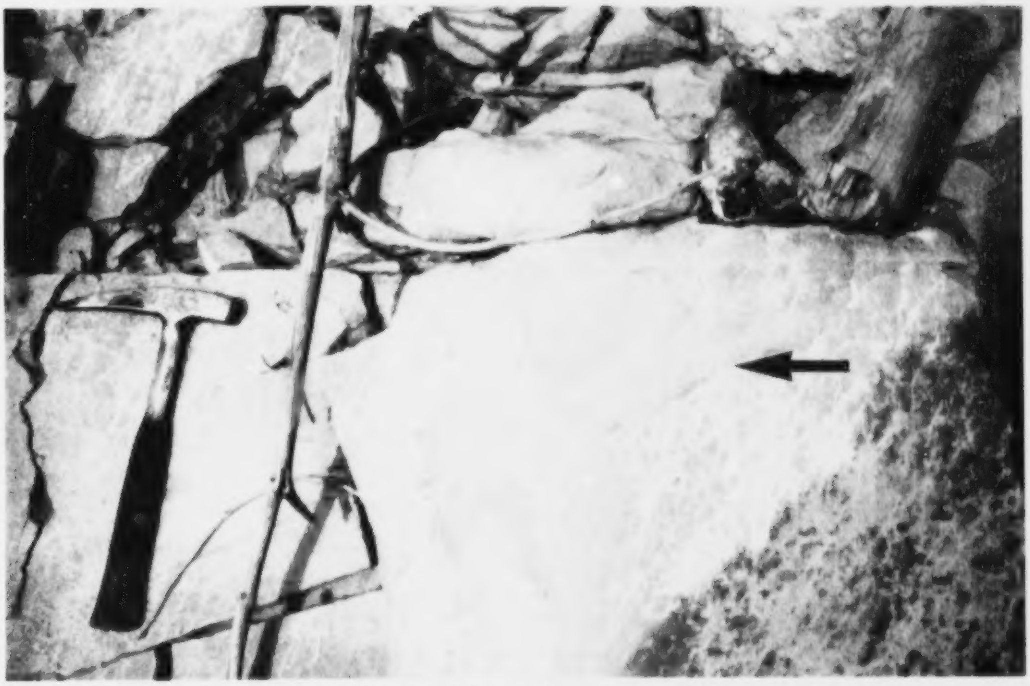


Plate 6. Planar-tabular cross-bedded (arrow) sandstone of facies E at the Brown Hill section. Hammer for scale is 25cm long.

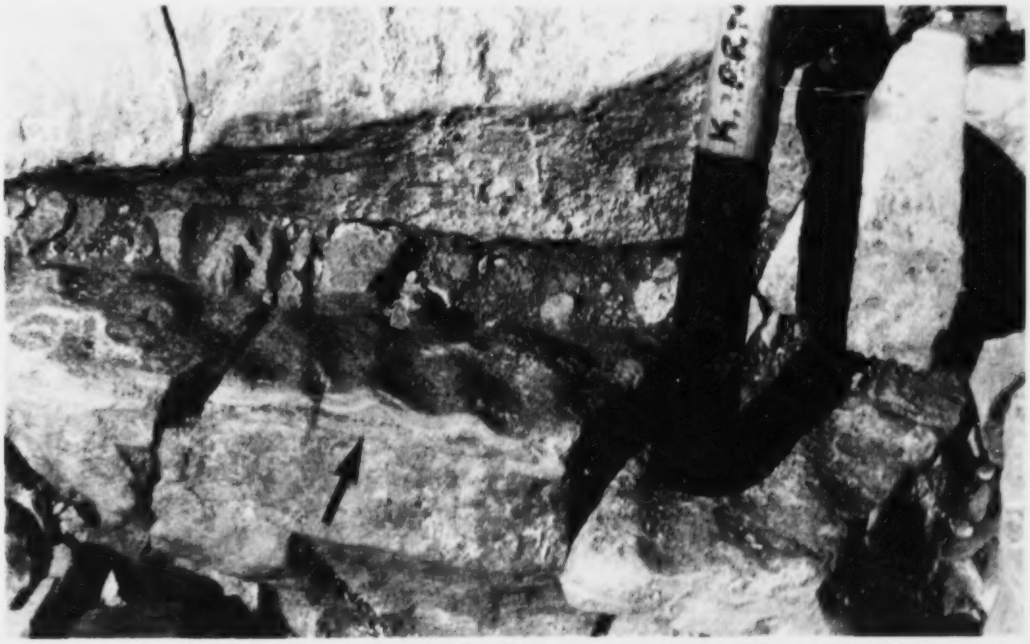


Plate 7. Supercritical climbing ripples (arrow) overlying planar-tabular cross-bedded sandstone of facies E at the Brown Hill section. Hammer for scale is 20cm long.

1992).

Facies E has a concave and erosive base, displaying features characteristic of channel sandstones (Weimer and Land, 1972). Facies in Triassic strata directly across Williston Lake from the Brown Hill section, displays channel sandstones with scoured bases containing rip-up clasts and shell valves, a fining upward grain size trend, a concave lower contact and a lense shaped sandstone geometry. These sedimentary features better display the typical inlet sequence (Moslow and Tye, 1985). Facies E is similar to interpreted tidal inlet sequences of subsurface Halfway Formation deposits (Willis, 1992; Caplan, 1992).

4.6.0 Facies F. Sandy Laminated Carbonate Mudstone

DESCRIPTION: The sandy laminated limestone consists of finely crystalline, 30cm thick, carbonate mudstone with laminations and layers of fine to coarse siliciclastic sandstone. The sand is structureless and is always overlain by structureless or occasional wavy laminated light and dark gray carbonate mudstone (Plate 8). The sandstone layers are yellow, buff, and reddish-orange, well sorted, very porous and have a calcite cement or matrix. The alternating beds of mudstone and sandstone are 2mm to 5cm thick. The sandstones can occur as lenses and are more prominent on weathered surfaces (Plate 9). In one occasion the mudstone limestone grades from sandy horizontally laminated mudstone into fine sandy symmetrical ripples of mudstone. The ripples have a wavelength of 6.5cm and an amplitude of 1cm. There are no observable fossils or trace fossils.

INTERPRETATION: Thick deposits of alternating sand and mud are characteristic features of repetitive waning flow conditions associated with tidal processes (Nio and Yang, 1991). The sands are deposited during periods of high current velocity while the muds are deposited by suspension during slack water conditions. The wave formed ripples show that deposition occurred in shallow water (Demicco, 1983). The mixture of mud and sand and the changeing current velocities are common features of tidal flats (Dalrymple, 1992). The transition from wavy bedding to lenticular bedding is common in tidal flat environments (Reineck and Singh, 1980) and is the result of the net decrease in current velocity and increased deposition of mud. Thus facies F was deposited in an intertidal environment. This lithofacies is important because it is a mixture of clastic and carbonate deposition and may mark the transition from clastic dominated deposition associated with the Liard (Halfway) shoreline to carbonate peritidal deposition of the Charlie Lake Formation.

4.7.0 Facies G. Sandy Cross-Bedded Carbonate Packstone

DESCRIPTION: The sandy cross-bedded carbonate packstone consists of carbonate

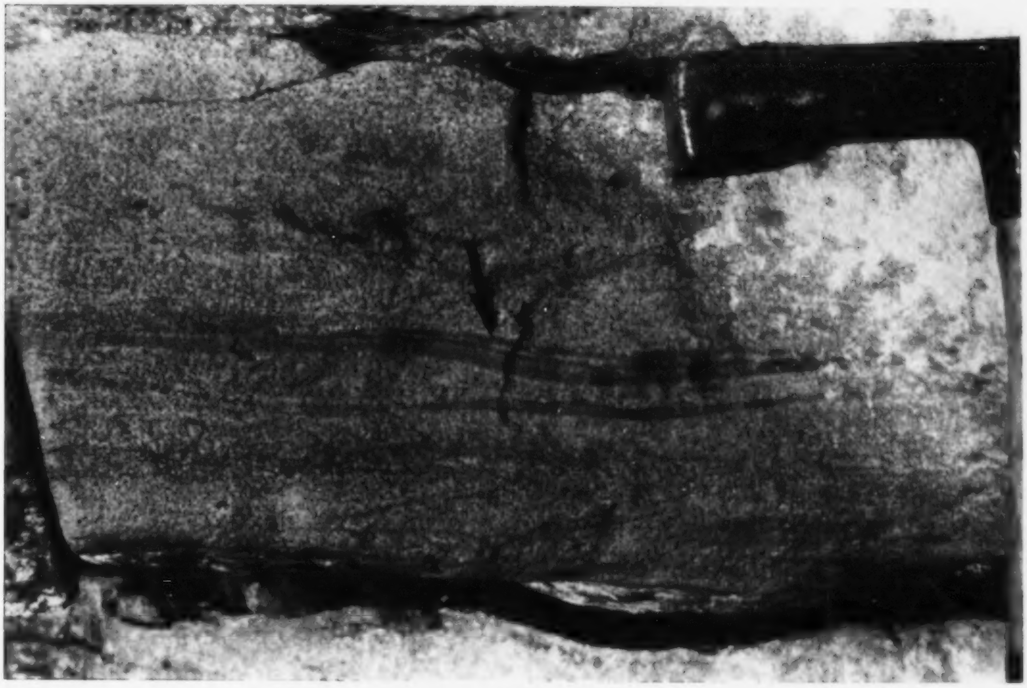


Plate 8. Wavy laminations (arrow) in sandy laminated carbonate mudstone of facies F at the Brown Hill section. Hammer head for scale is 9cm long.

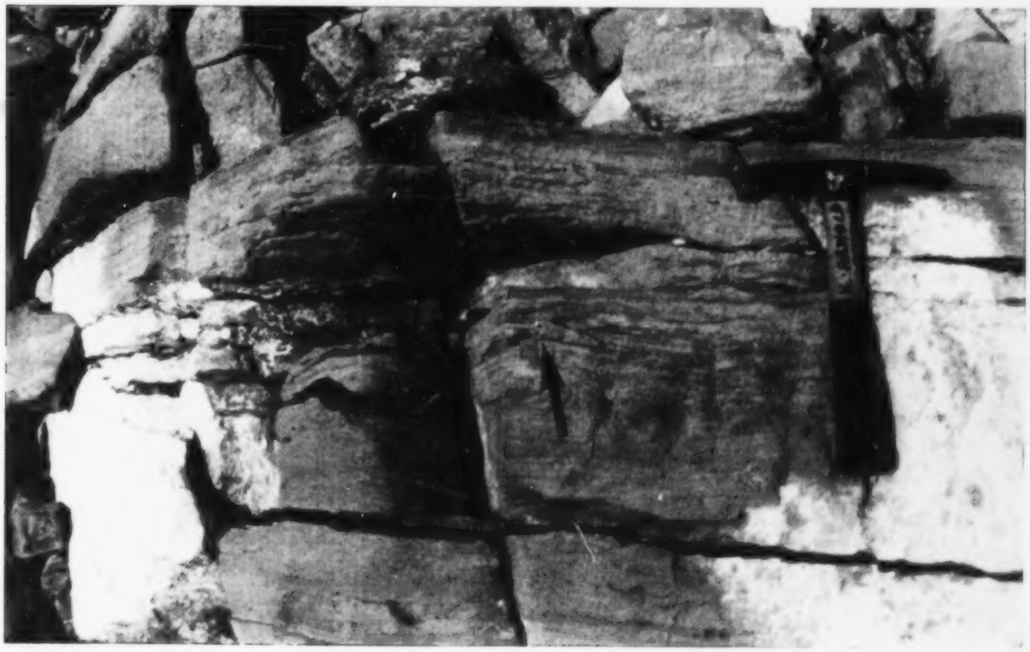


Plate 9. Iron stained sandstone lenses (arrow) in sandy laminated carbonate mudstone of facies F at the Brown Hill section. Hammer for scale is 25cm long.

mudstone with abundant fine to coarse sand. The facies is approximately 50% carbonate mudstone and 50% sandstone. The planar-tabular cross-beds are 10cm to 20cm thick and contain 1mm to 2mm laminations which are evident on weathered surfaces due to the resistance of the quartz grains (Plate 10). The cross-beds dip 5 to 15 degrees. Gastropod and bivalve fragments, crinoids and pebbles (2mm to 4 mm) were found at the base of one cross-bed. The shell fragments grade upward into the cross-beds of sandy carbonate packstone which are void of fossiliferous debris. The sandy cross-bedded carbonate packstone is interbedded with sandy laminated carbonate mudstone of facies F.

INTERPRETATION: The fining upward sequence in the cross-beds and the shell fragment and pebble lags at the base are characteristic of waning current flow in channel settings (Hayes, 1980; Shinn, 1983). The planar-tabular cross-beds are produced by lateral migrating of a channel (Cloyd et al., 1990). The subtidal environment is reinforced by the presence of gastropod, bivalve, and crinoid fragments at the base of the cross-beds. Facies G is interpreted as a tidal creek deposit. Even though tidal creeks on tidal flats are difficult to preserve (Pratt et al., 1992) a few ancient creeks have been identified (Pratt and James, 1986; Waters et al., 1989; Cloyd et al, 1990). Again the mixed clastic/carbonate lithology may mark the transition from clastic dominance to carbonate dominance.

4.8.0 Facies H. Massive Carbonate Mudstone

DESCRIPTION: The massive carbonate mudstone facies consists of light to dark gray, carbonate mudstone deposited in 2 to 4m thick beds. Some beds contain a minor amount of siliciclastic silt and very fine grained sand. The mudstones are massive in appearance and lack sedimentary structures or size grading. There are horizontal, irregular seams that run through the mudstones (Plate 11) and are possible stylolites. There are also many vug-like cavities that are 3mm to 7mm thick which are heterogeneously displaced. Some beds contain lenses of brecciated carbonate clasts within a sandy carbonate mudstone matrix. The brecciated clasts are angular, and lack any indication of imbrication or grading. Occasionally the facies grades from a skeletal wackestone into a mudstone. The massive mudstone facies commonly grades into the microbial laminated carbonate mudstones of Facies I. Facies H is occasionally overlain by laminated mudstones of Facies A by a sharp, wavy contact. Facies H occasionally overlies and erosionally truncates parts of the high angle cross-stratified sandstones of Facies K. When the massive carbonate mudstones of facies H overlie Facies K the lower part of facies H is sandier and also tends to be bioturbated.

INTERPRETATION: The massive and thick bedded appearance of facies H is the result of bioturbation by marine organisms (Hardie and Shinn, 1986). Even though no fossils or

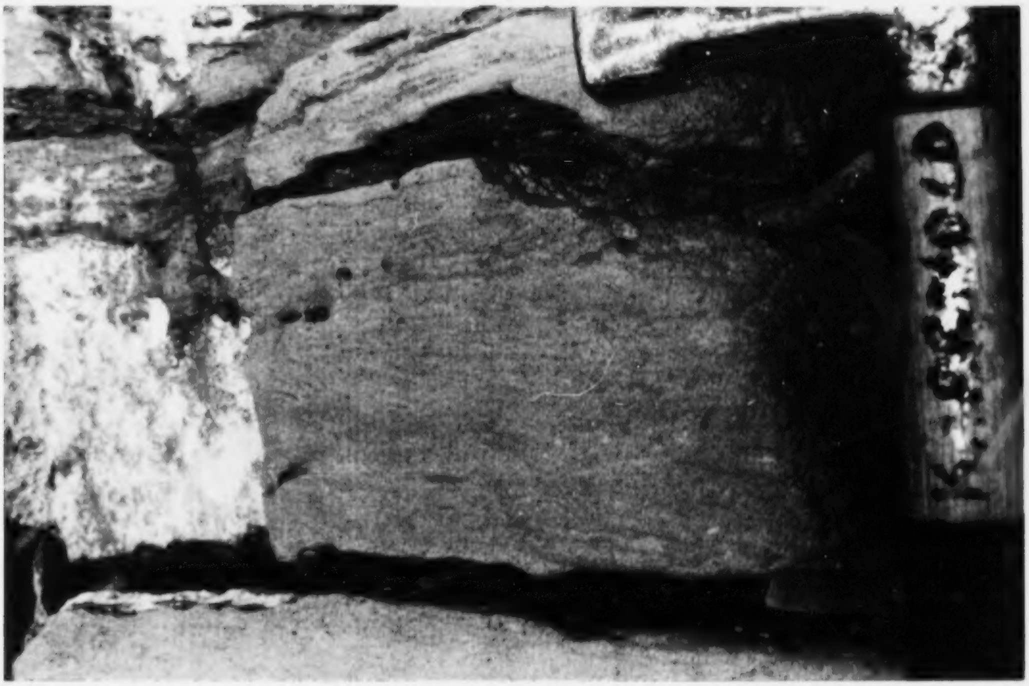


Plate 10. Sandy cross-bedded carbonate packstone of facies G at the Brown Hill section. Hammer for scale is 15cm long

Plate 11 . Massive carbonate mudstone with wispy silt laminations in facies H, Charlie Lake Formation, Brown Hill section. Hammer handle on the right is 20cm long.

traces are observed in the massive carbonate mudstone, the presence of skeletal wackestone bases indicates that some organisms did exist. The fossils and bioturbation are characteristic of sheltered low energy marine conditions in a subtidal environment. Interbeds of laminated shales (facies A) provides further support that the massive carbonate mudstones were deposited subaqueously by suspension deposition (Harms et al., 1982). The positioning and gradational nature of the massive carbonate mudstones beneath microbial laminated carbonate mudstones places the massive mudstones in the subtidal zone of common peritidal shallowing upward successions (Hardie and Shinn, 1986). The vug-like cavities may be dissolved evaporite crystals suggesting that these portions of the mudstones were deposited in the lower intertidal zone where gypsum or anhydrite can be precipitated. Facies I is interpreted as carbonate deposition in the subtidal portion of an lagoon situated in an arid climate.

The sand within the massive limestones is incorporated depositionally by several processes. The first is by storm processes. Sand and silt can be transported into the subtidal lagoon, where suspension deposition is dominant, by storm generated currents (Davis and Byers, 1989). The associated storm stratification is destroyed by burrowing organisms leaving a massive sandy or silty carbonate mudstone. Further evidence of storm deposition is provided by the presense of angular limestone intraclasts and the erosional contacts with underlying sandstones of facies K. The other process of silt and sand deposition into the carbonate mudstone occurs by the release of deflated sediments, transported offshore by suspension in wind, over the subtidal environment (Sarnthein and Diester-Haass, 1977; Chan and Kocurek, 1988).

4.9.0 Facies I. Microbial Laminated Carbonate Mudstone

DESCRIPTION: The microbial laminated facies consists of carbonate mudstone containing either crinkly, undulatory laminations or small, millimeter-size voids. The facies occurs in beds 1m to 2m thick. The millimeter sized voids are generally elongated horizontally and are in uniform rows giving the mudstone a laminated appearence. Some of the voids are filled with calcite. The crinkly, undulatory laminations tend to build upward creating domal highs within the mudstone (Plate 12). The draping of laminated mudstone of Facies A helps to identify the mounds. This facies forms beds 1-2m thick that commonly overlie and are gradational with facies H. The microbial laminated mudstones are usually overlain by solution breccias of Facies J. Because of the voids, porosity can be high within the intervals where evaporite cement leaching has occurred. No fossils or trace fossils have been observed.

INTERPRETATION: The irregular millimetre thick laminae, domal structures and mm

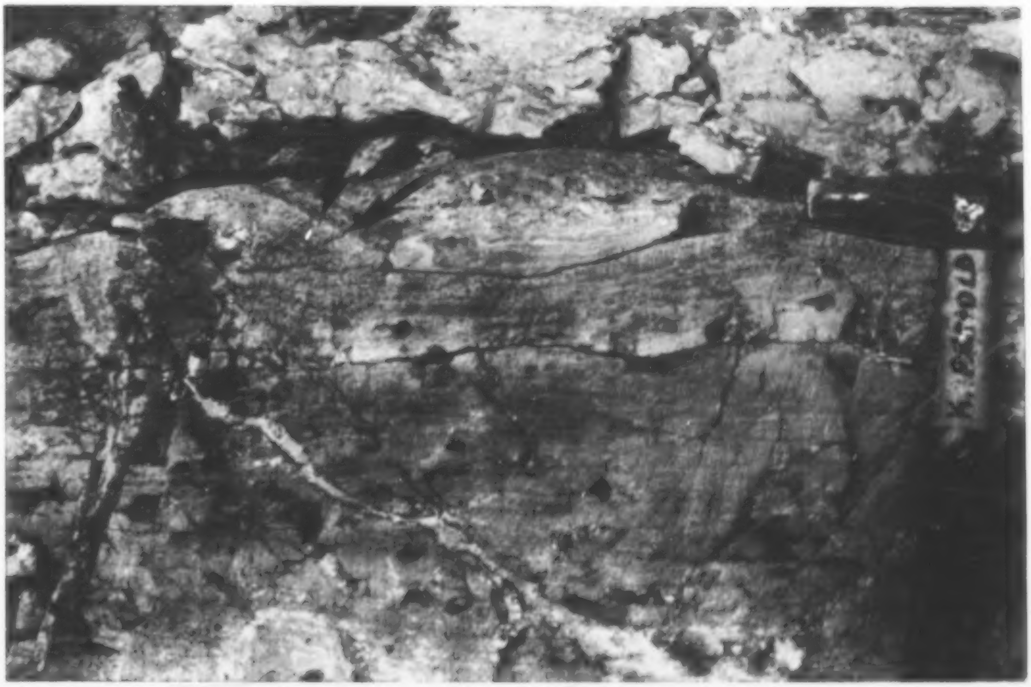


Plate 12. Domed algal laminations (arrow) in carbonate mudstone of facies I, Charlie Lake Formation, Brown Hill section. Hammer for scale is 25cm long.

sized voids (fenestral fabric) are features associated with present day sediments bound by algal mats (Logan et al., 1964; Kendall and Skipwith, 1968, 1969; Shinn, 1983; Hardie and Shinn, 1986). The present day Trucial Coast of the Persian Gulf has planar algal mats growing within the mid- to high- intertidal and lower supratidal zones (Kendall and Skipwith, 1969; Warren and Kendall, 1985). In an intertidal and supratidal setting the mats are frequently covered by sediment brought in by tidal activity depositing muds by suspension or by trapping sediment being carried in the wind. The mats then recolonize the sediment surface creating a laminated sedimentary deposit. The planar microbial mats are best preserved in the upper intertidal to lower supratidal zone where destruction and removal by organisms and wind deflation is at a minimum (Hardie and Shinn, 1986).

The presence of millimetre sized calcite filled and unfilled vugs are characteristic of fenestral fabric (Shinn, 1983) which is formed in present day supratidal flats of the Trucial Coast. The vugs form by shrinkage and expansion of sediments, gas bubble formation, escaping air during flooding, or as wrinkles in algal mats (Shinn, 1983). The vugs are preserved in supratidal settings because they are quickly lithified and filled with carbonate cement, internal sediments and evaporites. The unfilled vugs are probably the result of post-depositional leaching of evaporites (anhydrites). The fenestral fabric association with underlying microbial laminated carbonate mudstone and overlying solution breccias (facies J) would place the rock in the upper intertidal to lower supratidal zone where the vugs and algal mats would be preserved.

4.10.0 Facies J. Solution Collapse Breccia

DESCRIPTION: The solution collapse breccia consists of a carbonate mudstone matrix and clasts of various lithologies (Plate 13). The breccias occur in beds 30cm to 6m thick. The clasts are angular and range in size from 1cm to 21m. The breccias are generally matrix supported and have as little as 10% clasts or up to 60% clasts. The clasts usually consist of carbonate mudstone of Facies H but include clasts of microbial laminated carbonate mudstone (Facies I), and high-angle cross-bedded sandstone of Facies K. The solution breccia facies typically overlies microbial laminated carbonate mudstone of Facies I and is itself overlain by high-angle cross-bedded sandstone, massive carbonate mudstone, or microbial laminated carbonate mudstone. If the solution breccia is overlain by high-angle, cross-bedded sandstone, the breccia matrix can be sand dominant.

INTERPRETATION: The collapse breccias of Facies J are interpreted as the result of post-depositional leaching of evaporites (anhydrites). Evaporites are deposited in a wide range of depositional settings. In an arid peritidal setting, evaporites are deposited in subtidal (layered evaporites), to intertidal, and supratidal zones (Hardie and Shinn, 1986). If

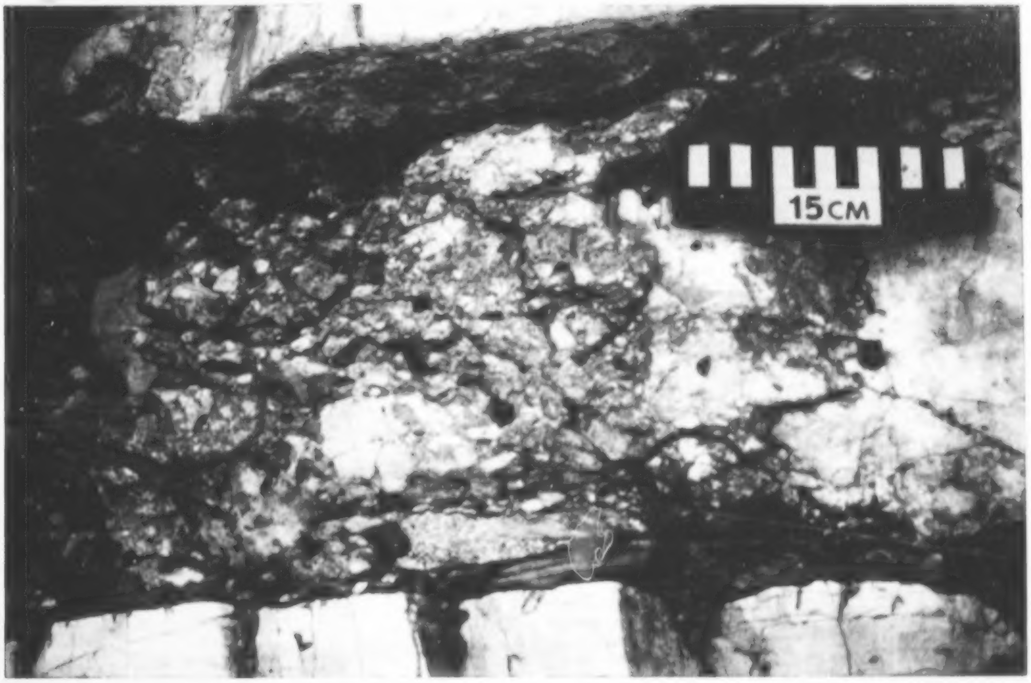


Plate 13. Solution breccia of facies J between two massive carbonate mudstones beds of facies H, Charlie Lake Formation, Brown Hill section. Scale bar for scale.

leaching occurred within a complete peritidal sequence (subtidal to supratidal), the evaporites (anhydrites) would be dissolved away leaving large cavities which under pressure of overlying rocks would collapse, forming a collapse breccia (Clifton, 1967). The breccia would contain clasts and fragments of subtidal, intertidal and supratidal carbonate mudstones. The breccia would now represent the entire peritidal sequence.

The collapse breccia interpretation is further substantiated by the presence of multiple horizons of laminated anhydrites and mosaic anhydrites in the subsurface strata of the Charlie Lake Formation which are lacking in outcrop. Also the subsurface Charlie Lake strata contains no collapse breccias. Breccias do exist in the subsurface, but are interpreted to have formed by desiccation. It is likely that evaporites were originally deposited in outcrop strata, but have been reworked and replaced by meteoric ground water (Middleton, 1961) during tectonic uplift forming the collapse breccias.

4.11.0 Facies K. High-Angle Cross-Stratified Sandstone

DESCRIPTION: This facies consists of reddish-orange to golden yellow, well sorted, fine-to medium-grained, large-scale, planar cross-stratified sandstone. The cross-beds are tabular to wedge shaped (Plate 14) and range from 20cm to 1.0m increasing in thickness from the base upwards. Most cross-beds are less than 0.5m thick. The cross-stratification occurs in cosets 0.75-4m thick separated by horizontal planar bounding surfaces or strata of facies M (Plate 15). Lower bounding surfaces are planar with the internal laminations running tangential (foreset dips of 0-30 degrees) to the planar surface. The lower bounding surfaces periodically have 5cm to 20cm thick beds of horizontal to low-angle (0 to 5 degrees), thinly (<0.3cm) inverse graded laminations. The tangential laminations of the cross-beds merge into the horizontal to low-angle inverse-graded laminations. Granules and coarse grained sand occasionally occur along the lower bounding surface.

The strata of the lower cross-beds of each coset contains 1.0cm to 4.0cm thick strata that consists of upper fine-to lower medium-grained, structureless sandstone, that tapers to a wedge down-dip. The wedge shaped strata dip at 20-30 degrees. The wedge toes overlie, and are overlain by, 1.0mm thick inverse graded laminations which disappear updip along the length of the thicker structureless strata. The inverse graded laminations display a distinct "pin striping" due to cement differentiation (Fryberger and Schenk, 1988). The strata of the upper cross-beds of each coset consists of lower angle (10-20 degree), thinly laminated, fine grained sandstone. The strata is dominated by the distinct, continuous, "pin striping" laminations and minor amounts of strata which are faint, discontinuous, change thickness laterally, and have varrying thicknesses from lamination to lamination. No body fossils or trace fossils are observable in this facies.

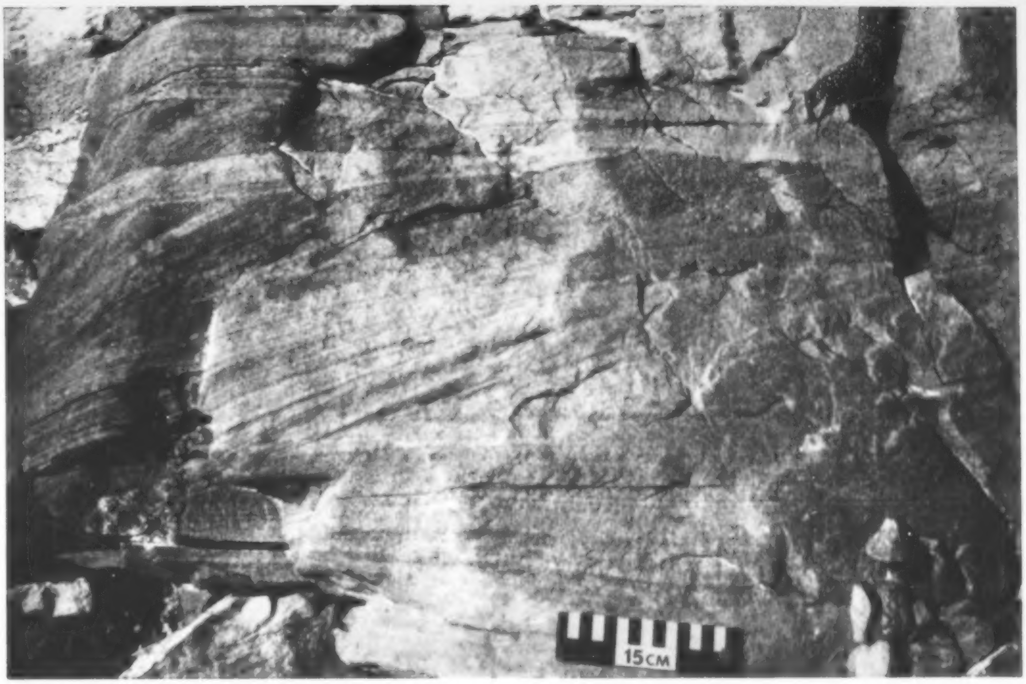


Plate 14. High-angle planar-tabular cross-bedded sandstone of facies K, Charlie Lake Formation, Brown Hill section. Scale bar for scale.

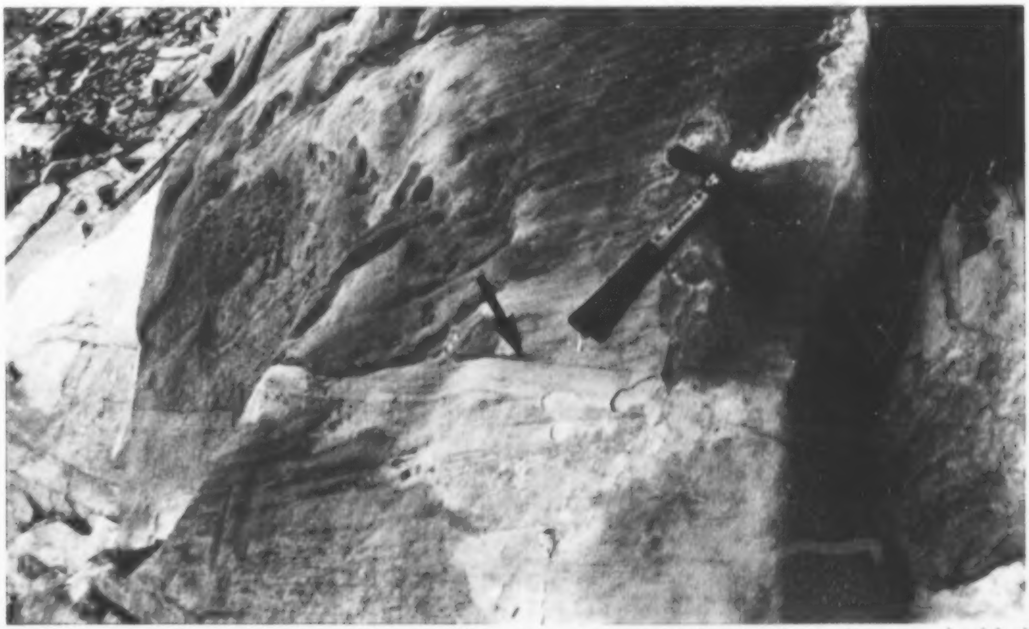


Plate 15. First-order bounding surface (arrow) separating high-angle cross-bedded sandstones of facies K, Charlie Lake Formation, Brown Hill section. Hammer for scale is 25cm long.

INTERPRETATION: The presence of uniform, thin, inverse graded laminations indicates aeolian deposition. The presence of thin, uniform, inverse grading within successive laminae is one of the best criteria for identifying laminae formed by wind ripples and is commonly restricted to aeolian depositional processes (Hunter, 1977; 1981; 1990). Inverse graded laminations form in many different aeolian subenvironments. They are the most common structure in aeolian sand sheets and in dry depositional interdune depressions (Fryberger et al., 1979). Wind ripple strata of sand sheets and interdunal areas tend to be horizontal to low angle. If the interdunal wind ripple strata is preserved, the structure (horizontal laminations) can be used to delineate bounding surfaces (Figure 33) within the aeolian sandstone body (Brookfield, 1977). The horizontal strata containing pin stripe laminations seen in outcrop are of this origin. Wind ripples are also common on the lee slopes of aeolian dunes, which are the portions of dunes most likely to be preserved (Hunter, 1977). Wind ripples occur on the apron at the base of the dune slipface and anywhere where the angle of repose on the slipface does not allow avalanching to occur. The high-angle (> 10 degrees) pin stripe laminations observed in outcrop represent migrating wind ripples on the lee slope of aeolian dunes.

The relatively thick (> 1 cm), lenticular, distinct, high-angle cross-strata of the lower cross-bed sets of the Charlie Lake sandstone units are another type of aeolian fine structure. Strata of this kind are produced by the avalanching of noncoherent sand down a dune slipface and is termed grainflow strata (Hunter, 1981). In sections parallel to the dip direction, the lenticularity is expressed as basal pinchouts or toes of the cross-strata (Hunter, 1977). The thin, inverse graded, pin stripe laminations that commonly overlie the grainflow strata are produced by migrating wind ripples on the grainflow surface between avalanche events. The wind ripple laminations pinch out updip due to the erosive nature of the next avalanche deposit.

The faint, discontinuous laminations common to the upper cross-bed sets of the sandstone units are interpreted as grainfall strata. Grainfall strata is produced in zones of flow separation, which occur leeward of dune crests (Hunter, 1977, 1981). They are best preserved on the mid-lee slope between the apron where wind ripples dominate and the crest where avalanching occurs (Kocurek and Dott, 1981). Strata of this type are rare as they are usually destroyed by avalanching sand from above. The thin, inverse graded, laminations associated with the grainfall strata are wind ripple strata which form when the wind stress increases on the lee slope (Hunter, 1990).

The coarse grained sand and granules found at the bases of high-angle cross-beds are interpreted as lag deposits on interdune flats (Kocurek, 1981; Pye and Tsoar, 1990). The clasts are too large for transport by wind so they remain as a deflationary deposit while the smaller sized particles are removed by traction, saltation, and suspension. The lag deposits are useful in determining bounding surfaces within the sandstone bodies (Kocurek, 1981).

4.12.0 Facies L. Contorted Sandstone

DESCRIPTION: The contorted strata of facies L consists of well sorted, fine-to medium-grained sandstone. The sandstone is folded (parabolic recumbent), disrupted, and complexly contorted (Plate 16). Most of the deformation is complexly contorted. The deformation occurs in units 1.5m to 1.8m thick. The lower contact is gradational with the cross-bedded sandstone of facies K while the upper contact is usually sharp and overlain by symmetrical ripples of facies M or carbonate mudstone of facies H. The contorted strata contain the distinct, thin "pin stripe" laminations that are characteristic of facies K (high-angle cross-bedded sandstone). No burrows or fossils were observed.

INTERPRETATION: The gradation of the contorted sandstone strata of facies L from undeformed high-angle cross-bedded sandstone indicates that the deformed sandstone is depositionally related to the adjoining aeolian cross-bedded sandstone, except that it has undergone post-depositional alteration. The presence of distinct, inverse graded, "pin stripe" laminations verifies the aeolian origin as the the laminations are a product of wind ripple migration and deposition (Hunter, 1977). Contorted and deformed sedimentary structures are common to aeolian deposits, both modern (Bigarella et al., 1969; McKee and Bigarella, 1972; McKee et al., 1971) and ancient (Horowitz, 1982; Doe and Dott, 1980; Glennie and Buller, 1983; Eschner and Kocurek, 1986; Huntoon and Chan, 1987); however the mechanism and origin of deformation may vary.

The deformation described in the Charlie Lake Formation sandstones is the same as the deformation described in the Weissliegend Sandstone by Glennie and Buller (1983). Glennie and Buller (1983) cite partial preservation and limited reworking of the dunes resulted from a rapid marine transgression, and that deformation occurred both during the flooding and after the dunes had been submerged. Aeolian sands have high porosities and permeabilities (Hunter, 1977) due to the processes of deposition which account for the large quantities of entrapped air (Glennie and Buller, 1983). As the dune sands become water saturated during the initial stages of transgression, the air is forced upward. The internal expression of this failure is in the form of complexly folded and contorted structures up to the water / sediment interface (Glennie and Buller, 1983). This mechanism of deformation would explain why the deformation is continuous to the top of the dune sequence (expulsion of air) and why it is gradational with undisturbed aeolian cross-beds below.

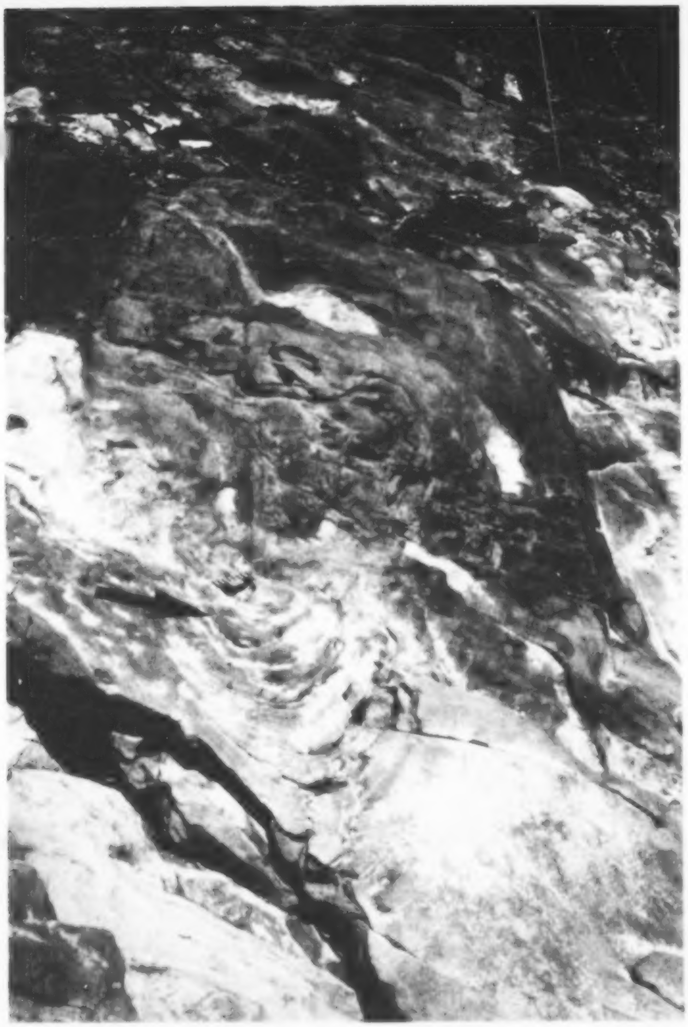


Plate 16. Contorted sandstone of facies L (arrow) overlying high-angle cross-bedded sandstone of facies K, Charlie Lake Formation, Brown Hill section. Contorted horizon is 2.0m thick.

The deposition of carbonate mudstone of facies H above the contorted sandstone is evidence that the dunes were flooded or transgressed (Kocurek, 1981; Glennie and Buller, 1983). The dune sands become saturated due to the transgression which results in the deformation of the sands. The presence of wave ripples (facies M) at the top of aeolian sequences indicates that the dune tops were slightly marine reworked during the transgression (Huntoon and Chan, 1987).

4.13.0 Facies M. Oscillation Rippled Sandstone

DESCRIPTION: This facies consists of symmetrically rippled, light brown to reddish-orange, very fine-to fine-grained sandstone (Plate 17). Silt and clay are present in small amounts and increase in abundance upwards within the ripples. Some of the ripples are in phase and others bifurcate when found on bedding surfaces. This facies forms in beds 10cm to 1.5m thick. Facies M is rarely dispersed in massive carbonate mudstones of facies H. The lower contact with facies H is gradational while the upper contact is sharp in the shape of the ripple bedform. The oscillation rippled sandstone is commonly overlain by massive carbonate mudstone of facies H. Facies M is also interbedded with and overlies Facies K. When Facies M is interbedded with Facies K the contacts are sharp. When Facies M overlies Facies K the contact is wavy in the cross-sectional shape of the symmetrical ripples. Some of the bedding surfaces are extensively horizontally burrowed. *Palaeophycus* is the dominant trace fossil.

INTERPRETATION: The facies is subaqueous in origin due to its symmetrical ripple shape, ichnology, and stratigraphic positioning. Oscillation ripples are formed by shoaling waves which reach the substrate in shallow water (Harms et al., 1982) above mean fairweather wavebase. Such shoaling can occur on the shoreface of barrier shorelines, or in lagoons and lakes. Stratigraphic positioning of facies M is used for interpreting its environment of deposition. The positioning below subtidal carbonates of facies H indicates the rippled sandstone was probably deposited in a shallow marine setting. The abundance of low diversity horizontal trace fossils is expected in an arid lagoonal environment in which the water is hypersaline (Davis, 1983).

When the wave rippled sandstone is interbedded within facies K, the oscillation rippled sandstone may be deposited in a lacustrine environment. Since the lacustrine sandstones are deposited between aeolian dunes of facies K, the sandstones are interdunal (Pye and Tsoar, 1990). The temporary interdunal lakes probably form during storm floods or high tides which rework the interdune areas and the lower slopes of the dunes (Hummel and Kocurek, 1984). At Padre Island, Texas, symmetrical ripple marks were confined to the waters edge, where small wind generated waves lapped on to the interdune pond shoreline

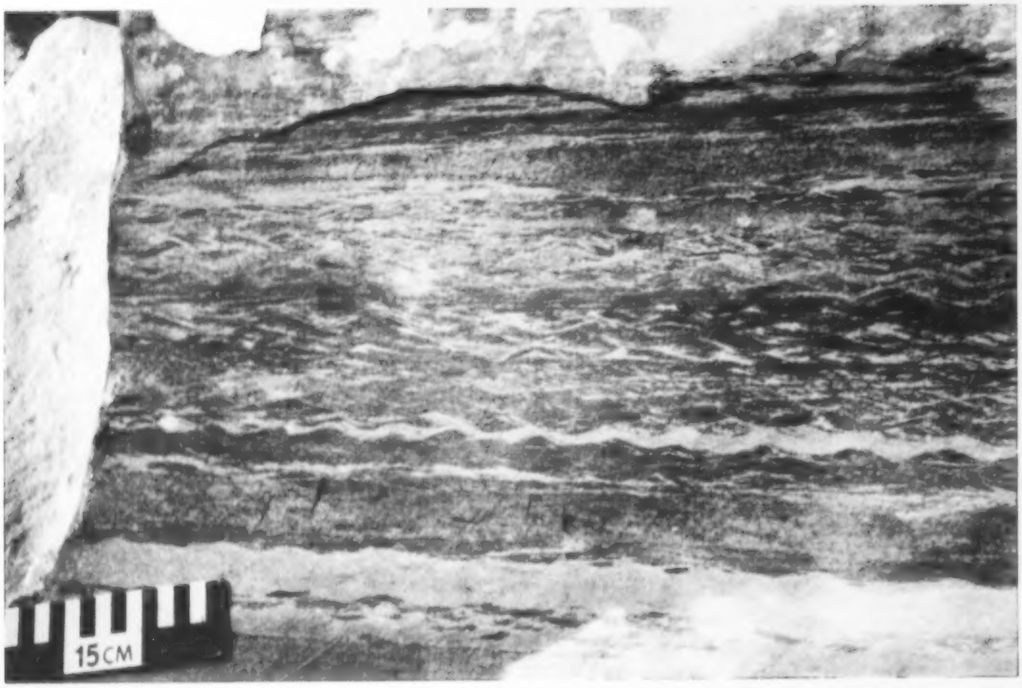


Plate 17. Symmetrical rippled sandstone interbed of facies M within high-angle cross-bedded sandstone of facies K (not shown in photo), Charlie Lake Formation, Brown Hill section. Scale bar for scale.

(Kocurek, 1981). A variety of interference ripples were present along interdune pond edges where runoff and waves produced interferring sets. The interdunal lakes eventually dry up (evaporation and run-off) and are overlain by prograding aeolian dunes (Ruegg, 1983). The fines deposited within the lakes may be deflated when exposed to the wind or scoured and deflated by the prograding dunes leaving the oscillation rippled sandstone with a sharp upper contact.

4.14.0 Facies N. Low Angle Laminated Silty Carbonate Mudstone

DESCRIPTION: This facies consists of light to dark brown, silty, carbonate mudstone in beds that are 10cm to 50cm thick. The silt grains are only visible on weathered surfaces where it is displayed as fine wavy parallel laminations in beds dipping 0 to 10 degrees (Plate 18). The lower contact is abrupt and undulatory with chert filled diapiric highs and fossiliferous (gastropod and bivalves?) wackestone lows which grade into the low angle silty laminated carbonate mudstone. The mudstone is occasionally interbedded with 1.0cm to 2.0cm thick medium grained sandstone beds which are laterally discontinuous. There are also 7.0cm to 30cm thick bioturbated horizons with identafiable *Diplocraterion, Rhizocorallium, Planolites* and *Teichichnus* trace fossils. The carbonate mudstone contains quartz-and calcite-lined and filled vugs that are up to 10cm in diameter.

INTERPRETATION: The silty, carbonate mudstone contains an open marine fauna of gastropods and bivalves, as well as crinoids (Gibson and Edwards, 1990). The Cruziana ichnofacies also indicates a subtidal setting in which deposition occurs below fairweather wave base but above storm wave base (Pemberton et al., 1992). The mudstone texture with occasional wackestone layers indicates a low wave energy, setting. However, the low angle laminations with bioturbated tops and possible wave ripples is characteristic of storm deposition (Kreisa, 1981). In shallow waters, periodic scour by storm waves followed by renewed deposition after the storm may incorporate storm layers within a sequence of otherwise low-energy deposits (Pemberton and Frey, 1984). The tops of the storm deposits are reworked by organisms after the substrate returns to normal fair weather conditions. The lower contact, with the diapiric structures, may be produced by the rapid loading of unconsolidated sediments causing fluid escape and upwelling (Williams, 1960). Such rapid deposition can be caused by sediment loading during storms. The vugs are possible fossils or evaporite nodules which have dissolved. Facies N represents a deepening event after deposition of Charlie Lake peritidal facies and is interpreted to have been deposited in an open marine environment.

Plate 18. Horizontal laminations of silt in carbonate mudstone of facies N, Baldonnel Formation, Brown Hill section. Hammer for scale is 25cm long.

5.0.0 BROWN HILL FACIES ASSOCIATIONS

The Triassic outcrop section at Brown Hill summarized in Figure 19 has three recurring vertical facies associations (Table 3). The first facies association consists of a gradational upward-coarsening sequence displaying storm, current and wave action, truncated by numerous fining-upward channel deposits. Facies association 1 is interpreted as a deposit of a barrier island shoreface cut by numerous tidal inlet channels. Facies association 2 is a shallowing upward sequence interpreted as a peritidal sequence capped by aeolian dunes. The aeolian dunes display a variance within facies association 2. The third facies association consists of shallowing upward cycles interpreted as open marine shelf deposits.

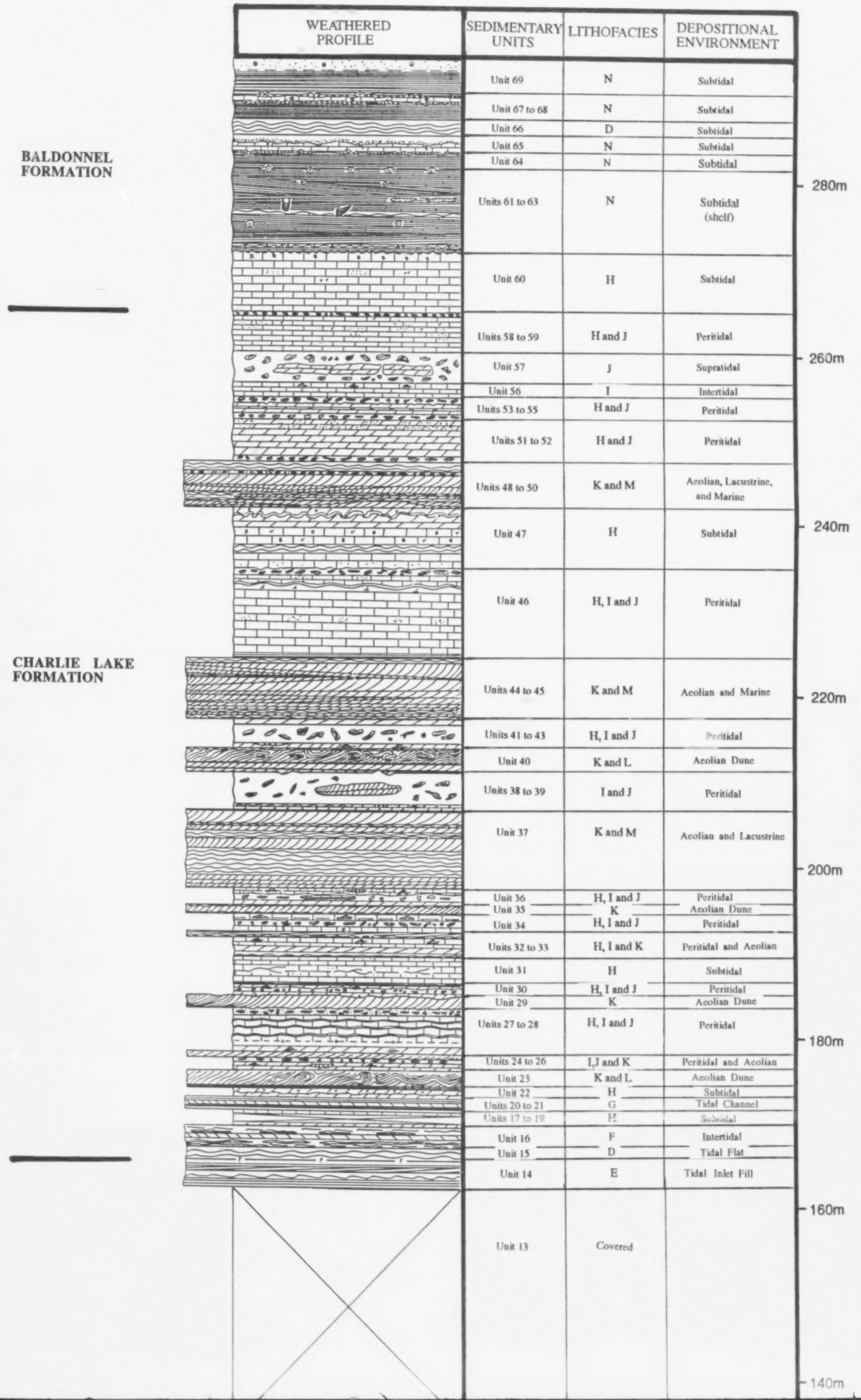
The following chapter describes the depositional origin of these facies associations and compares them to modern and ancient analogues. The vertical and lateral variations of the facies associations and their relationship to each other are also discussed.

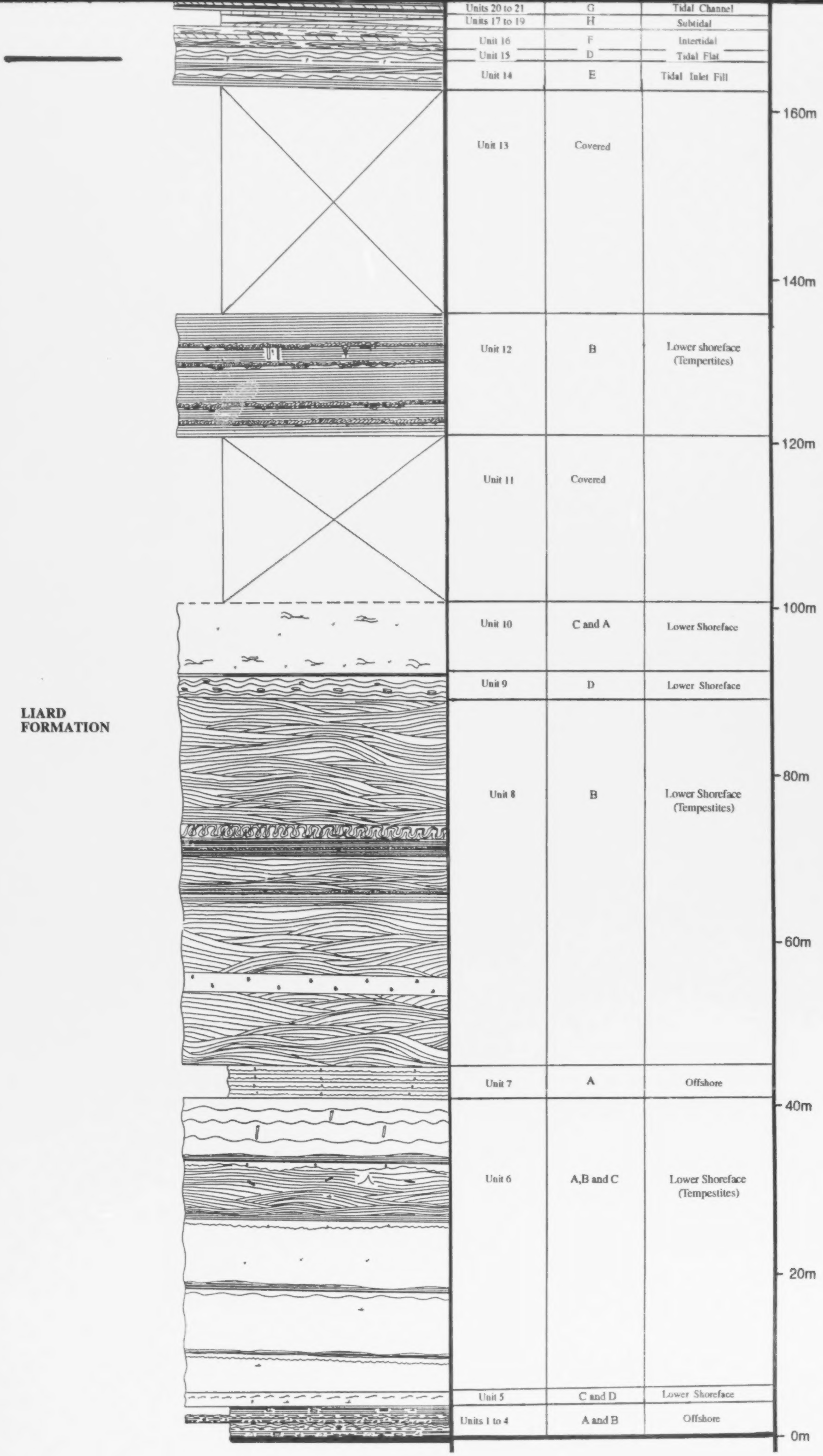
5.1.0 Facies Association 1: Storm Shoreface with Tidal Inlet Channels

Facies association 1 consists of a conformable fining upward sequence comprising Facies B to D then A which is erosionally truncated by a fining upward sequence of Facies E and D (Figure 20). In the Brown Hill section, facies A to D is repeated several times while the tidal inlet channel facies of E and D only occurs at the top of the repeated storm shoreface (facies A to D) sequences. Facies association 1 is overlain by facies association 2.

The base of facies association 1 is placed at the base of Facies B. The sandstones of facies B always have sharp and occasionally erosive bases which truncate laminated shales of facies A or similar sandstones of facies B and C. Internally the sandstones display fine horizontal laminations and hummocky cross-stratification which occasionally have shale rip-up clasts at the base. When facies B erodes into facies B it produces stacked or amalgamated deposits of hummocky cross-stratification.

Hummocky cross-stratification (HCS) is believed to be formed by strong surges of varying direction that are generated by relatively large storm waves of a rough sea acting below fairweather wave base (Harms et al., 1975). A depositional origin below fairweather wave base is commonly believed because the HCS is frequently interbedded with bioturbated mudstones and the sandstones have not been reworked by fairweather processes. The sandstones of facies B are commonly interbedded with laminated shales showing bioturbation and seldom display wave generated structures indicating deposition below fairweather wave base. However it should be noted that some HCS has been deposited at depths of 2m off the modern Oregon coast (Hunter and Clifton, 1982) meaning HCS can also be deposited above fairweather wave base as high as the upper shoreface.




LIARD FORMATION
Units 20 to 21
G
Tidal Channel
Units 17 to 19
H
Subtidal
Unit 16
F
Intertidal
Unit 15
D
Tidal Flat
Unit 14
E
Tidal Inlet Fill
Unit 13
Covered
Unit 12
B
Lower shoreface (Tempertites)
Unit 11
Covered
Unit 10
C and A
Lower Shoreface
Unit 9
D
Lower Shoreface
Unit 8
B
Lower Shoreface (Tempestites)
Unit 7
A
Offshore
Unit 6
A,B and C
Lower Shoreface (Tempestites)
Unit 5
C and D
Lower Shoreface
Units 1 to 4
A and B
Offshore
160m
140m
120m
100m
80m
60m
40m
20m
0m

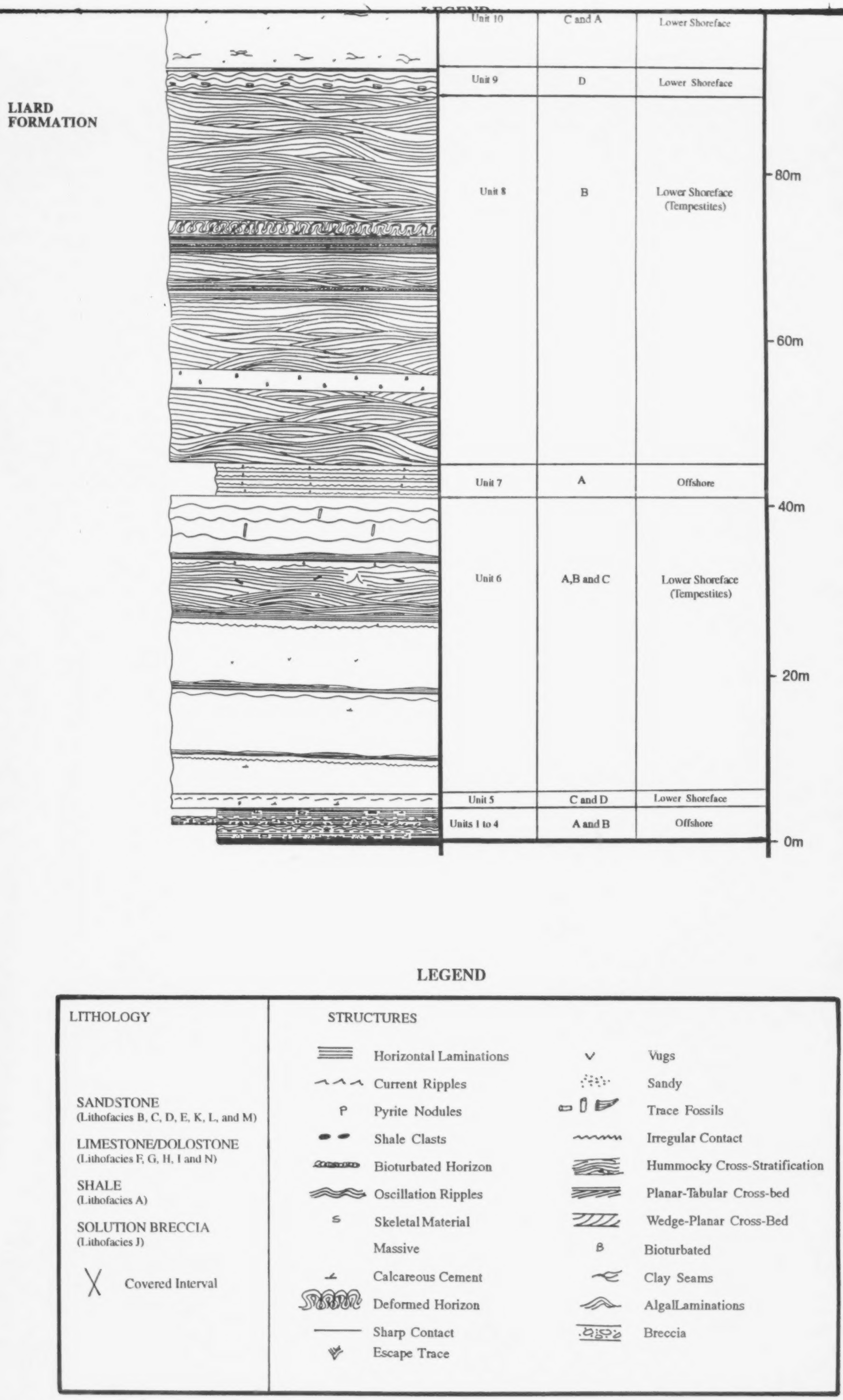

LIARD FORMATION
Unit 10
C and A
Lower Shoreface
Unit 9
D
Lower Shoreface
Unit 8
B
Lower Shoreface (Tempestites)
Unit 7
A
Offshore
Unit 6
A,B and C
Lower Shoreface (Tempestites)
Unit 5
C and D
Lower Shoreface
Units 1 to 4
A and B
Offshore
80m
60m
40m
20m
0m
LEGEND
LITHOLOGY
SANDSTONE (Lithofacies B, C, D, E, K, L, and M)
LIMESTONE/DOLOSTONE (Lithofacies F, G, H, I and N)
SHALE (Lithofacies A)
SOLUTION BRECCIA (Lithofacies J)
Covered Interval
STRUCTURES
Horizontal Laminations
Current Ripples
Pyrite Nodules
Shale Clasts
Bioturbated Horizon
Oscillation Ripples
Skeletal Material
Massive
Calcareous Cement
Deformed Horizon
Sharp Contact
Escape Trace
Vugs
Sandy
Trace Fossils
Irregular Contact
Hummocky Cross-Stratification
Planar-Tabular Cross-bed
Wedge-Planar Cross-Bed
Bioturbated
Clay Seams
AlgalLaminations
Breccia

Figure 19. Strip log of the Liard, Charlie Lake and Baldonnel formations providing the lithologies, sedimentary structures, and interpreted environments of deposition as described at the Brown Hill section.

Facies Association 1 Shoreface Cut by Tidal Inlets		**Facies Association 2** Aeolian Capped Peritidal	
Facies	Environment	Facies	Environment
F	Backbarrier (Intertidal)	M	Marine Reworked Aeolian Dune
D	Tidal Inlet	L	Aeolian Dune
E	Tidal Inlet	K	Aeolian Dune
D	Lower shoreface	J	Peritidal (Supratidal?)
C	Lower shoreface	I	Peritidal (Intertidal)
B	Lower Shoreface	H	Peritidal (Subtidal)
A	Offshore	G	Tidal Channel
		F	Tidal Flat

Table 3. Halfway and Charlie Lake formations Facies Associations.

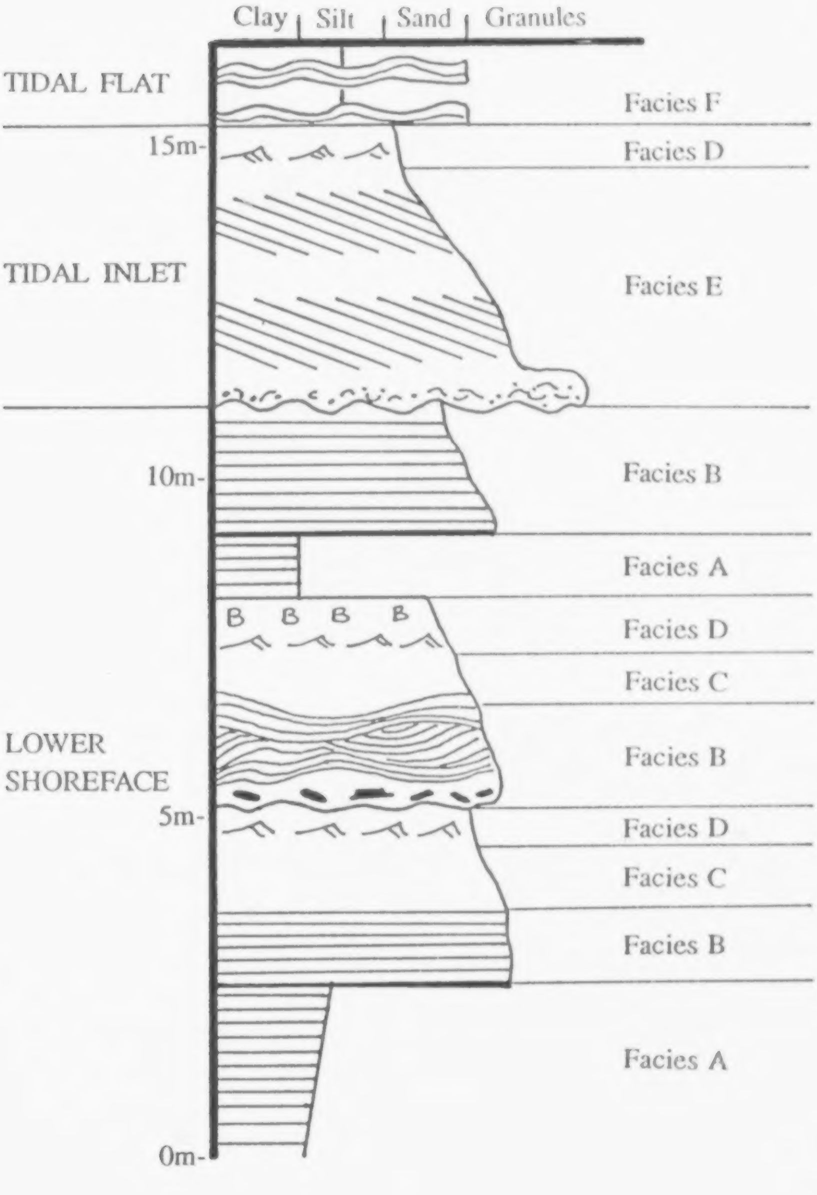

Clay
Silt
Sand
Granules
TIDAL FLAT
TIDAL INLET
LOWER SHOREFACE
15m-
10m-
5m-
0m-
Facies F
Facies D
Facies E
Facies B
Facies A
B B B B
Facies D
Facies C
Facies B
Facies D
Facies C
Facies B
Facies A

Figure 20. Facies association 1 of lower shoreface and tidal inlet deposits interpreted at the Brown Hill section.

The tops of the HCS sandstone beds are frequently bioturbated by grazing organisms indicating a return to fair weather conditions. Where the tops of these beds are not bioturbated, facies B grades vertically into current rippled sandstones of facies D.

Massive sandstones of facies C are interpreted to have been deposited in the same manner as sandstones of facies B. Facies C is commonly interbedded with sandstones of facies B ; when it is not interbedded with facies B the sandstones have sharp bases and frequently bioturbated tops. Like facies B, facies C commonly grades vertically into current rippled sandstone of facies D.

Sandstones of facies B and C are commonly overlain by ripple laminated sandstones of facies D. The ripples are asymmetrical and exhibit cross bedding indicative of unidirectional currents. Such currents could be generated by storms or possibly longshore currents. The ripples gradationally overlie hummocky cross-stratified sandstones of facies B and therefore probably represent waning flow conditions.

When the hummocky cross-stratified sandstones are not amalgamated they are overlain by, or interbedded with laminated shales of facies A. These shale beds, were likely deposited after each storm event. Where facies A has been eroded by the a subsequent storm event, the HCS sandstone beds are amalgamated. Facies A is a product of suspension deposition in the offshore environment. The finely laminated shales were deposited by mud and silt falling out of suspension and accumulating on the sea floor below fairweather but above storm wave base. Deposition above storm wave base is indicated by the interbeds of hummocky cross-stratified sandstones. The abundance of trace fossils and brachiopods suggests that the substrate was aerobic.

The storm-dominated lower shoreface to offshore facies are overlain by a large covered interval in outcrop. Facies E is the first strata that reappears at the end of the covered interval. The facies contains low-angle, planar cross-beds that are capped by ripple laminated sandstone of facies D. Sedimentary structures of facies E and D infer current deposition. The transition from planar cross-beds to current ripples indicates a waning of flow. The ripple laminations of the fining upward sequence are capped by peritidal facies of facies association 2.

The same fining upward sequence of facies D and E is observed in Triassic strata directly across Williston Lake from the Brown Hill section. The sandstone beds here have erosional bases and contain bioclastic fragments and rip up clasts along the base. Trough and planar cross-beds grade into current ripples in association with a fining upward grain

These sedimentary characteristics infer a waning current flow. This facies succession is in erosional contact with shoreface deposits. The fining upwards trend, erosive base, and stratigraphic position of the facies D-E succession is characteristic of tidal inlet channel fills (Figure 21). Such inlet fill sequences are common to the Halfway Formation and have been identified by Caplan (1992) and Willis (1992).

The depth of inlet scour depends upon a number of factors including the hydrographic regime. Due to the extent of the covered interval, the depth of inlet erosion is not known. The inlet may scour down into upper shoreface deposits or as deep as the lower shoreface and offshore. Those inlets that migrate laterally may remove a large portion of the laterally adjacent shoreface. The tidal inlet sequences observed in this study are interpreted to have scoured down into the lower shoreface deposits. The covered outcrop intervals represent stacked tidal inlet channel fills. Detailed descriptions, interpretations and discussion of the variations in Halfway shorelines and their lateral facies relationships are given by Willis (1992) and Caplan (1992).

In summary, facies association 1 represents a regressive barrier island shoreface sequence that is truncated by tidal inlet channels. The deep, thick tidal inlet successions and the dominance of storm deposits offshore indicate that the Halfway shoreline was storm wave and tidally influenced.

5.2.0 Facies Association 2: Back-barrier Arid Peritidal Shoreline

Facies association 2 consists of a shallowing upward peritidal sequence comprising facies F, G, H, I, J, K, L, and M. There are variations to the shallowing upward sequences, therefore not all facies are present in each shallowing upward cycle. Tidal flats are subdivided into three depositional-ecological zones as a result of daily tidal oscillations (Figure 22). The supratidal zone occurs above mean high water and is only flooded by seawater during spring high tides and storm surges. The intertidal zone occurs between mean high water and mean low water and is flooded and exposed daily by tidal activity. The subtidal zone occurs below mean low water and is always submerged except during strong offshore winds in which the upper subtidal portion will be exposed.

5.2.1 Subtidal to Supratidal Sequence

The common shallowing upward sequence that occurs at Brown Hill comprises facies H, I and J (Figure 23). In a complete cycle the sequence always starts with the massive carbonate mudstone of facies H. Facies H rarely displays any sedimentary structures. Occasionly, a symmetrical wave ripple is present indicating current transport by an oscillatory flow. Because tidal flats are in wave protected settings, the sheltered

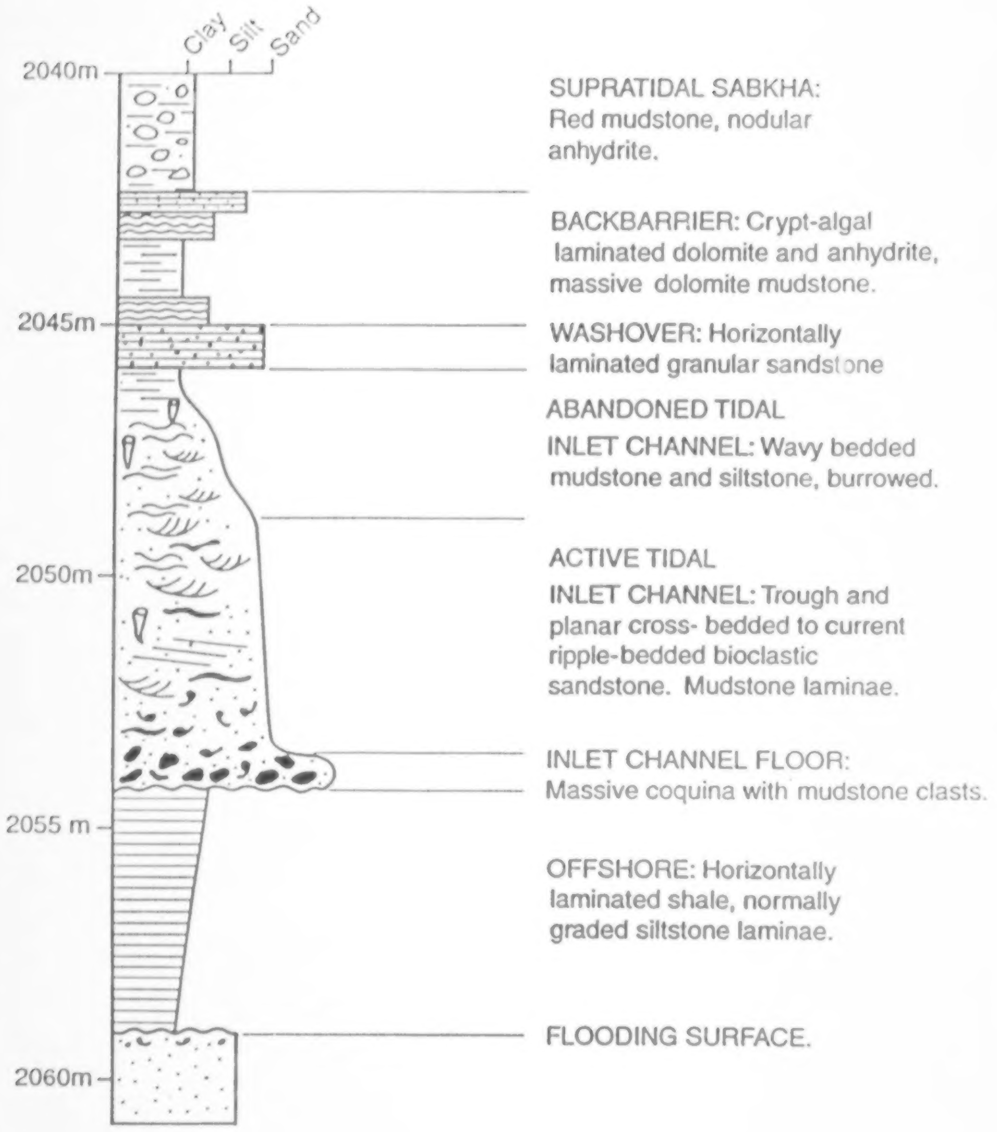

Clay
Silt
Sand
2040m
2045m
2050m
2055 m
2060m
SUPRATIDAL SABKHA: Red mudstone, nodular anhydrite.
BACKBARRIER: Crypt-algal laminated dolomite and anhydrite, massive dolomite mudstone.
WASHOVER: Horizontally laminated granular sandstone
ABANDONED TIDAL INLET CHANNEL: Wavy bedded mudstone and siltstone, burrowed.
ACTIVE TIDAL INLET CHANNEL: Trough and planar cross- bedded to current ripple-bedded bioclastic sandstone. Mudstone laminae.
INLET CHANNEL FLOOR: Massive coquina with mudstone clasts.
OFFSHORE: Horizontally laminated shale, normally graded siltstone laminae.
FLOODING SURFACE.

Figure 21. Tidal inlet sequence from the Halfway Formation interpreted from core in well 6-31-72-7W6 in Wembley Field, Alberta showing the common succession and sedimentary structures associated with typical tidal inlet deposits (modified after Willis, 1992).

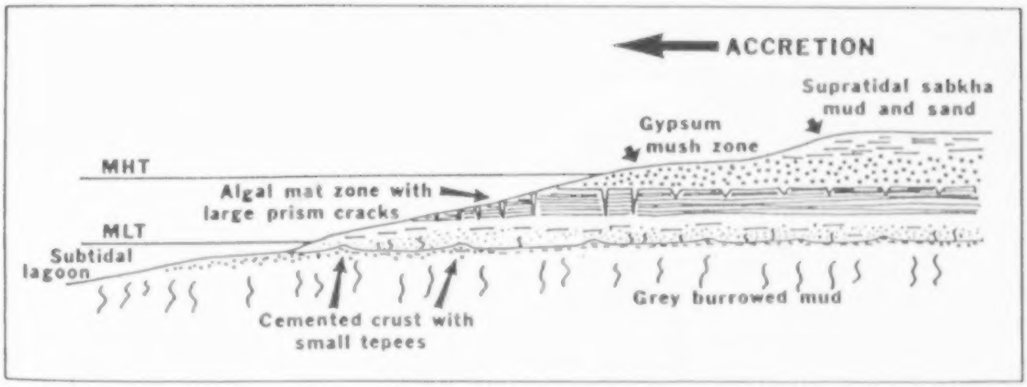

ACCRETION
Supratidal sabkha mud and sand
Gypsum mush zone
MHT
Algal mat zone with large prism cracks
MLT
Subtidal lagoon
Grey burrowed mud
Cemented crust with small tepees

Figure 22. Cross-section showing the division of peritidal zones based on tidal oscillations. MHT=mean high tide; MLT=mean low tide (modified after Hardie and Shinn, 1986).

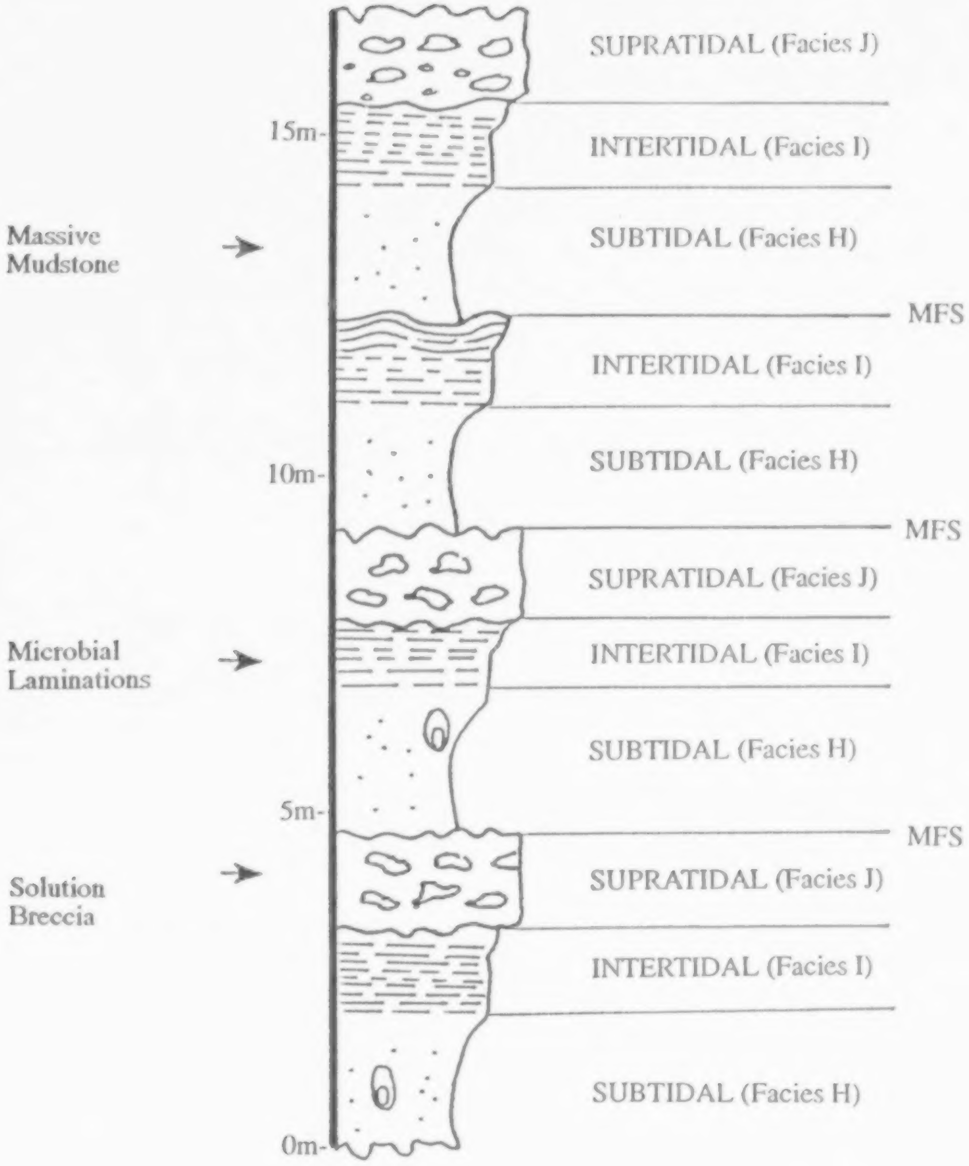

SUPRATIDAL (Facies J)
15m-
INTERTIDAL (Facies I)
Massive Mudstone
SUBTIDAL (Facies H)
MFS
INTERTIDAL (Facies I)
10m-
SUBTIDAL (Facies H)
MFS
SUPRATIDAL (Facies J)
Microbial Laminations
INTERTIDAL (Facies I)
SUBTIDAL (Facies H)
5m-
MFS
Solution Breccia
SUPRATIDAL (Facies J)
INTERTIDAL (Facies I)
SUBTIDAL (Facies H)
0m-

Figure 23. Facies association 2 of peritidal deposits consisting of subtidal, intertidal and supratidal deposits interpreted in the Charlie Lake Formation at the Brown Hill section. MFS= marine flooding surface.

environment is a preferential site for mud accumulation (Hardie and Shinn, 1986). The muddiest sediments are deposited in the deepest part of the lagoon while the coarser sediments are deposited at the lagoonal margins where wind and wave action is more pronounced. The offshore mud is transported shoreward onto the tidal flats by tidal currents and onshore storms. Modern arid subtidal muds are gray in color due to sulfate-reducing bacteria and are structureless due to the abundant grazing organisms (Hardie and Shinn, 1986).

As the sequence shallows upward, facies H is overlain by facies I. Facies I consists of microbial laminated mats dispersed in massive gray limy mud. Present day intertidal flats of the Persian Gulf have black well laminated algal mats occurring in the upper part of the intertidal zone. The algal mats gradually disappear and merge into gray muds of the subtidal zone where salinities are more normal and hospitable for gastropod grazing (Figure 24). The upper intertidal zone is hypersaline, and is thus a harsh environment for marine organisms, thus preserving the mats from burrowing. This means that no definite contact can be placed between the subtidal and intertidal zones as lower intertidal deposits are identical to subtidal deposits. Original evaporite (gypsum altered to anhydrite) deposition is confined to the upper intertidal zone and increases in abundance towards the supratidal zone. However, as the peritidal cycle progrades seaward the intertidal and subtidal zones become overlain by evaporitic rich sediments of the supratidal zone. As a result, the intertidal and subtidal sediments start to precipitate gypsum rosettes leaving the sediments with secondary evaporitic deposition. The many vug like holes observed in facies H and I carbonate mudstones may have been formed by evaporites which have been dissovled.

Most evaporite deposition is restricted to the supratidal zone which overlies the intertidal zone. The climate in arid settings, such as the Persian Gulf, is so dry that algal mats are prevented from growing on the supratidal flats. Thus, the characteristic deposits of a dry, arid supratidal flat, exposed for long periods of time and only frequently flooded, is anhydrite with desiccation features. However, the mud polygons produced by desiccation are quickly eroded and removed by aeolian processes leaving anhydrite as the single common supratidal indicator. Anhydrite deposition on the Trucial coast (Kendall, 1992) occurs as layers or as massive accumulations consisting of nodules separated by sediment leaving a "chicken wire" fabric (Figure 25). Solution breccias of facies J are interpreted as dissolved evaporites (anhydrite). Most of the solution breccias are thick (1m). Since the thickest deposits of anhydrite deposition occurs within the supratidal zone in modern arid coastal settings, it is likely the solution breccias are supratidal zone facies. However, as discussed in the facies J interpretation, intertidal and subtidal sediments can also be associated with anhydrite deposition and upon dissolution can be changed into solution

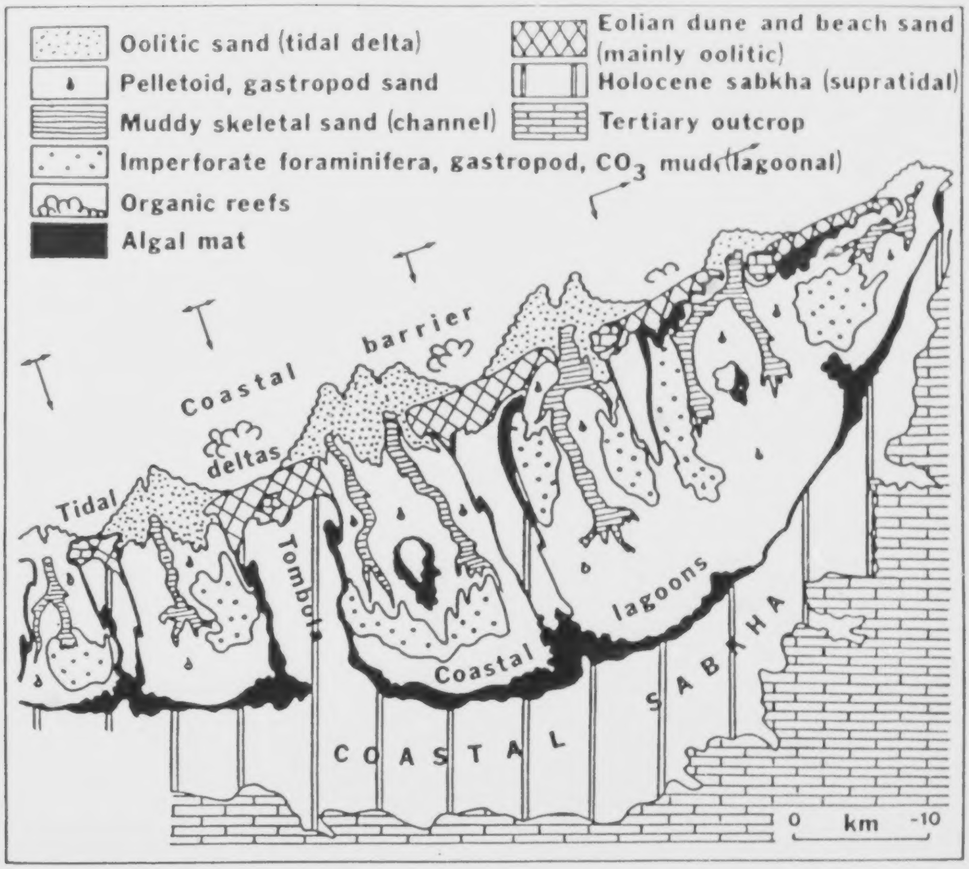

Oolitic sand (tidal delta)
Pelletoid, gastropod sand
Muddy skeletal sand (channel)
Imperforate foraminifera, gastropod, CO_3 mud (lagoonal)
Organic reefs
Algal mat
Eolian dune and beach sand (mainly oolitic)
Holocene sabkha (supratidal)
Tertiary outcrop
Tidal
Coastal
deltas
barrier
Tombolo
Coastal
lagoons
COASTAL
SABKHA
0
km
-10

Figure 24. Detailed depositional facies of the Trucial Coast tidal flats near Abu Dhabi. Offshore arrows show degree and direction of longshore drift (modified after Hardie and Shinn, 1986)

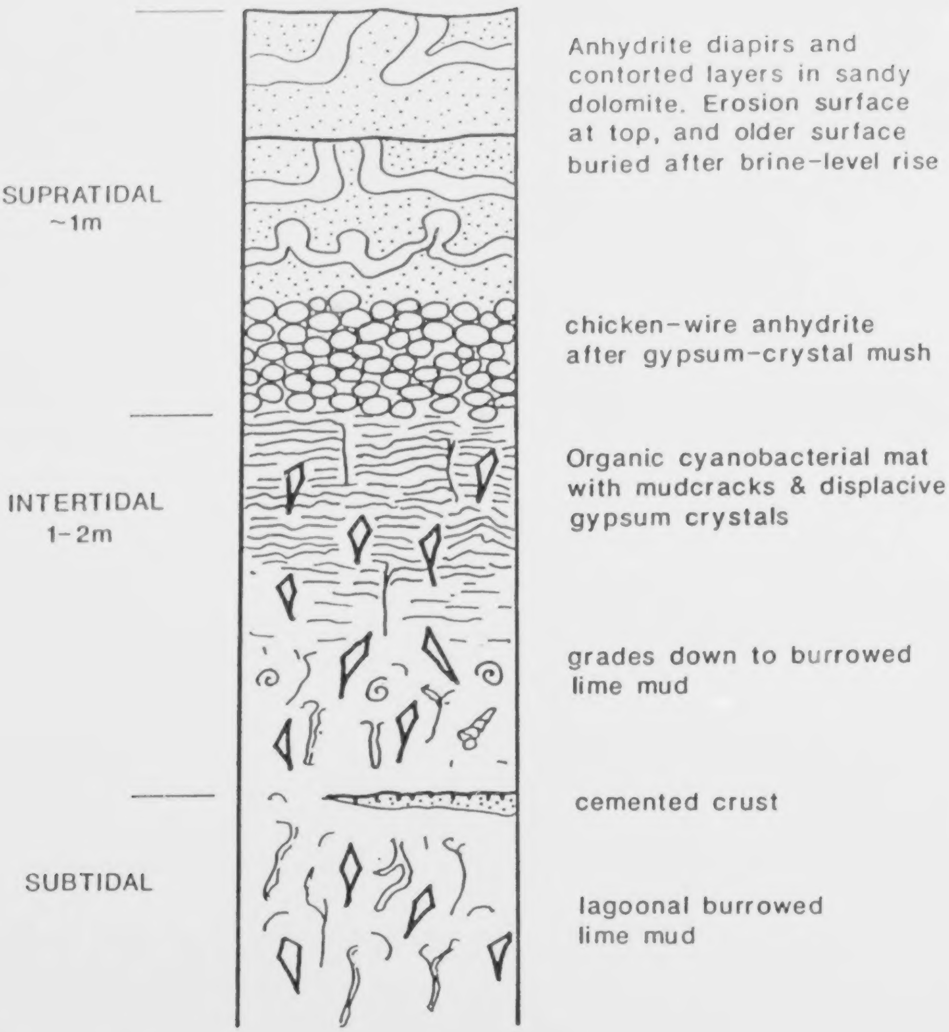

SUPRATIDAL
~1m
INTERTIDAL
1-2m
SUBTIDAL
Anhydrite diapirs and contorted layers in sandy dolomite. Erosion surface at top, and older surface buried after brine-level rise
chicken-wire anhydrite after gypsum-crystal mush
Organic cyanobacterial mat with mudcracks & displacive gypsum crystals
grades down to burrowed lime mud
cemented crust
lagoonal burrowed lime mud

Figure 25. Simplified vertical section through a typical sabkha sequence at Abu Dhabi displaying the sediment type and structures associated with each facies (modified after Kendall, 1992).

breccias meaning that a solution breccia can represent a complete peritidal cycle.

The peritidal cycle is not always complete (facies H,I and J). Sometimes a cycle may not shallow enough for supratidal deposition, and when flooded is overlain by subtidal sediments (Figure 23). So a small section may have a cycle of H, I and J facies, overlain by another cycle of just H, and I facies, and then overlain by a complete cycle of H, I and J facies.

5.2.2 Variations of the Subtidal to Supratidal Sequence

Facies H, I and J are the common reoccurring lithofacies in the peritidal sequence. The exception of this sequence is the deposition of facies F and G near the Charlie Lake Formation and Halfway Formation contact (Figure 19). In place of the intertidal microbial laminated carbonate mudstone, a sandy laminated carbonate mudstone occurs. The wavy and flaser bedding in the sandy laminated carbonate mudstone is characteristic of modern clastic intertidal deposits (Figure 26). The postioning between intertidal deposits of facies F suggests facies G is a tidal channel deposited within backbarrier tidal flats and not as a tidal inlet channel through a barrier island. Facies G would have been deposited in the subtidal zone and covered by facies F during progradation of the tidal flat.

The positioning of facies F and G near the clastic dominated Halfway shoreline and the base of the carbonate dominant Charlie Lake Formation may explain the mixture of sand and carbonate mud. In this setting, the sand supply is still abundant and tidal currents supply the sand to the arid tidal flats. The sand is deposited during strong current flows and carbonate mud is deposited during slack water conditions.

5.2.3 Lateral Facies Relationships of the Peritidal Sequences

The lateral facies relationships of the modern Persian Gulf will be used for interpreting the lateral facies relationships of the peritidal cycles in the Charlie Lake Formation. The Persian Gulf is ideal because the climate and depositional setting are similar to the interpreted climate and depositional setting of the Charlie Lake Formation. Most important, the Persian Gulf has aeolian dunes that prograde over the supratidal (sabkha) flats. As a result, some of the characteristics of the Persian Gulf may be analogous to Charlie Lake deposition.

Tidal flats of the Persian Gulf have grown in volume and area since the Holocene. The tidal flats parallel the shoreline (Figure 24) and are controlled by sea level. The flats have been able to grow by progradation. The shallow water conditions of tidal flats favour progradation because small volumes of sediment are needed to keep sediment accretion

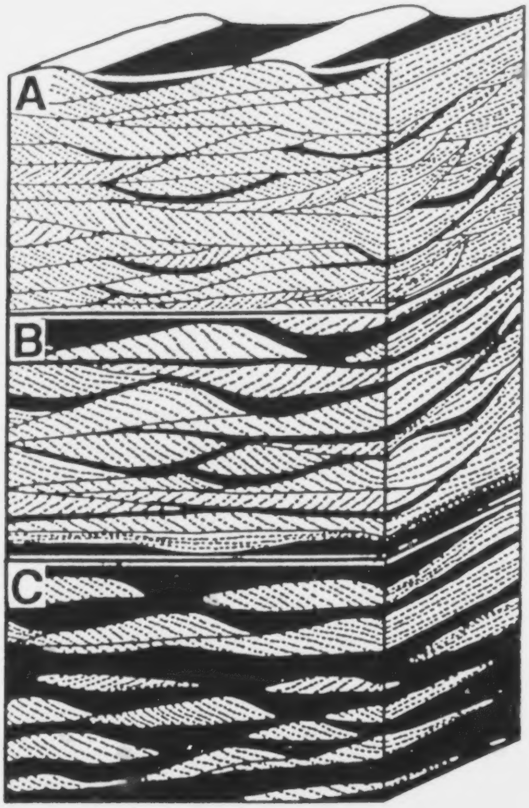


Figure 26. Flaser (A), wavy (B) and lenticular (C) bedding common to present day tidal flat deposition. The progression from A to C results from a net decrease in current velocity and increased preservation of mud drapes (modified after Reineck and Singh, 1980).

ahead of sea-level rise. The tidal flats prograde laterally into the backbarrier subtidal lagoon as sheet like deposits of subtidal, intertidal and supratidal facies (Figure 27). The Persian Gulf tidal flats have been estimated to have prograded at a maximum rate of 2km/1000 years (Kinsman, 1969). The size of the tidal flats are important because the extent of the flats limit the extent of the overlying seaward prograding aeolian dunes.

The whole tidal flat succession is wedge shaped with the landward margin wedging out into continental siliciclastic deposits and the seaward margin wedging out into the shelf-lagoon carbonate deposits (Figure 27). The peritidal succession thickens laterally towards the subtidal lagoon. As the peritidal deposits prograde, the supratidal flat (sabkha) constantly increases with size, thus creating a larger inland margin and transport distance for migrating aeolian dunes.

5.2.4 Aeolian Capped Peritidal Sequences

Periodically, the subtidal to supratidal sequences are overlain by, or interfingered with, aeolian dune sandstones of facies K and L. Deposition of aeolian and marginal marine facies is common in the rock record with documented examples from the Tensleep Sandstone of Wyoming (Mankiewicz and Steidtmann, 1979), the Quadrant Sandstone of Montana (Saperstone and Ethridge, 1984), the Morgan Formation of Utah and Colorado (Driese and Dott, 1984), the Schnebly Hill and Coconino Formations of Arizona (Blakey and Middleton, 1983), the Yeso Formation in New Mexico (Stanesco, 1991), the Minnelusa Formation of Wyoming (George, 1984; Desmond et al., 1984; Fryberger, 1984), and the Rico and Cedar Mesa Formations of Utah (Loope, 1984; 1985). Each of these examples have been interpreted as coastal aeolian deposits based on interbedding with marine deposits. Nine such occurrences have been identified in the Charlie Lake Formation at the Brown Hill section (Figure 19). Occasional deposition of aeolian sand at the top of the peritidal sequence (Figure 28) suggests that there was a fluctuating sand source and that there was a stillstand in sea level to allow erg progradation over the supratidal flats.

The aeolian sandstones are of variable thickness. This may be a reflection of sand supply, the length of sea level stillstand, wind speed and duration, and/or the rate of marine transgression (Figure 29). A rapid high energy transgression would modify and only partially rework and remove aeolian deposits nearly preserving paleotopography and structures (Huntoon and Kamola, 1988). A rapid transgression would leave a thick marine sequence over the aeolian strata. A slow high-energy transgression would extensively rework and completely destroy aeolian paleotopography while slow low-energy transgressions would preserve interfingering of marine and aeolian strata (Huntoon and Kamola, 1988). The interfingering nature of marine and aeolian facies in the Brown Hill

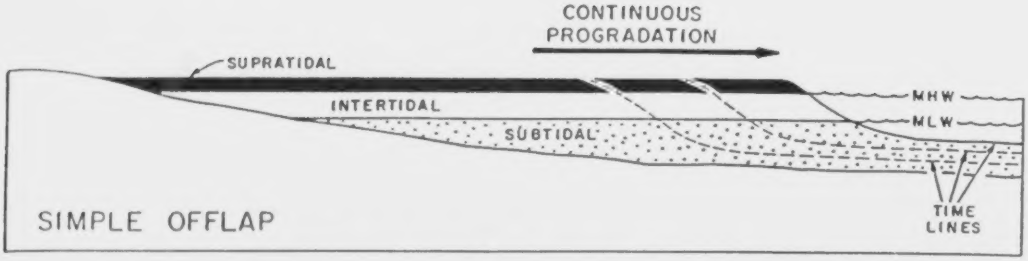

CONTINUOUS PROGRADATION
SUPRATIDAL
INTERTIDAL
SUBTIDAL
MHW
MLW
SIMPLE OFFLAP
TIME LINES

Figure 27. Progradation of subtidal, intertidal and supratidal deposits in a coastal setting. The peritidal deposits wedge out both landward and seaward (modified after Hardie and Shinn, 1986).

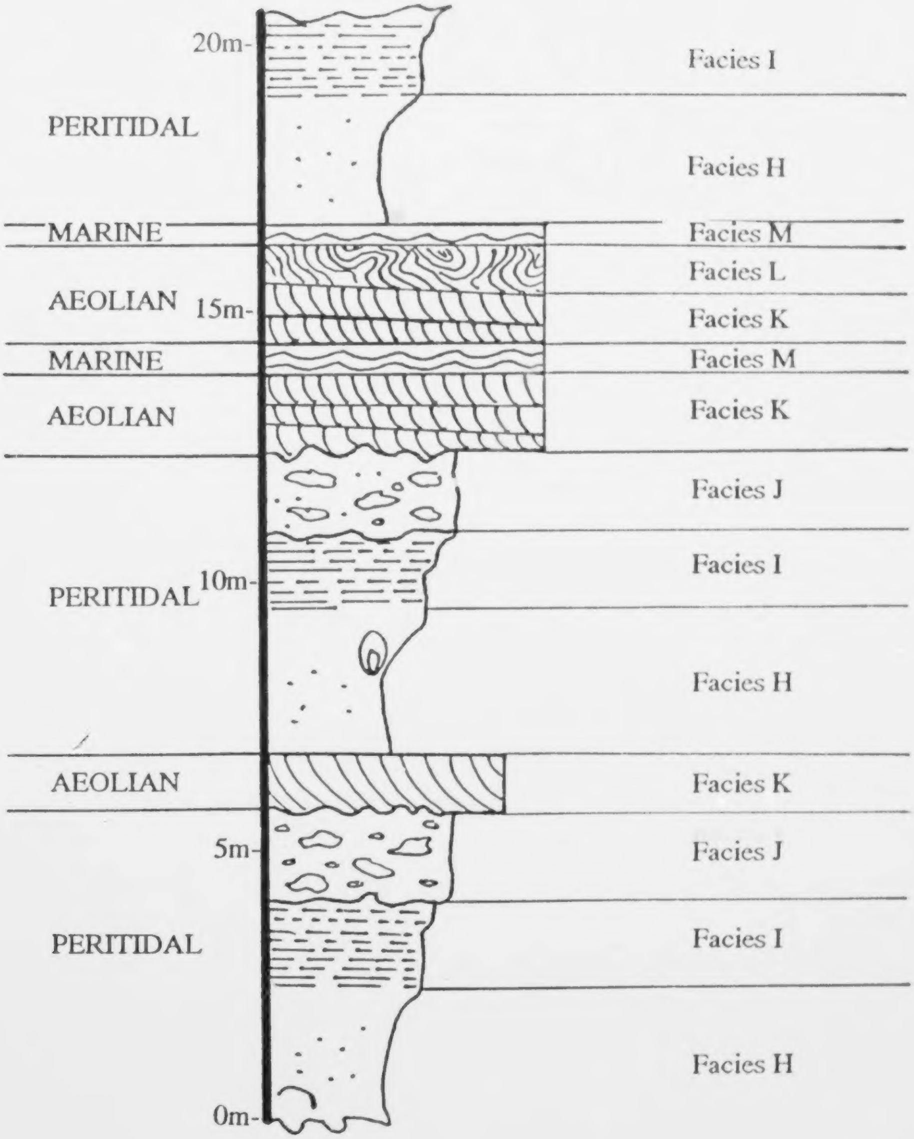

20m-
15m-
10m-
5m-
0m-
PERITIDAL
MARINE
AEOLIAN
MARINE
AEOLIAN
PERITIDAL
AEOLIAN
PERITIDAL
Facies I
Facies H
Facies M
Facies L
Facies K
Facies M
Facies K
Facies J
Facies I
Facies H
Facies K
Facies J
Facies I
Facies H

Figure 28. Aeolian capped peritidal succession of facies association 2 of the Charlie Lake Formation as interpreted from the Brown Hill section.

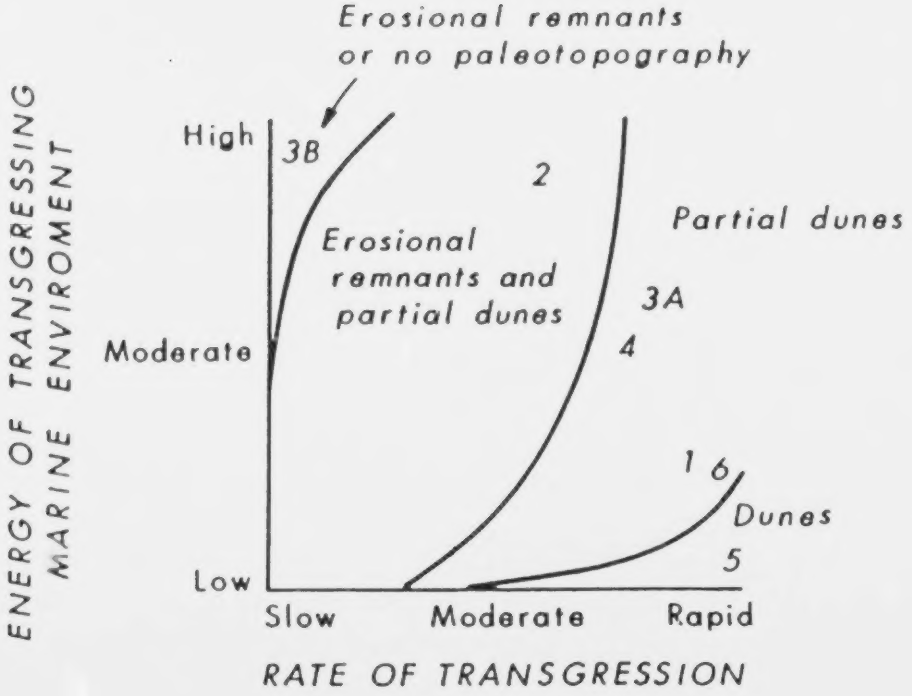


Figure 29. Relationships of energy and rates of marine transgressions over ergs and the preservation potentials of paleotopography. Examples are: (1) coastal Australia; (2) Entrada, northeastern Utah; (3A,B) Entrada, southwestern Colorado and northeastern New Mexico; (4) Weissliegend-Rotliegend, Poland; (5) Weissliegend-Rotliegend, England; (6) Minnelusa, Wyoming, (modified after Chan and Kocurek, 1988).

section suggests sea level rise was slow and of low-energy.

The aeolian sandstones generally increase in thickness upward through the Brown Hill section. The lower sandstones are 0.4 to 1m thick and consists of a single cross-bed while the upper sandstones are 3 to 9m thick and consist of multiple cross-beds and show the greatest variation in aeolian lithofacies. These thicker sandstones consist of facies K, L, and M and will be used in the discussion of a typical aeolian capped peritidal sequence (Figure 28).

The thicker aeolian sandstones display small scale cross-bedding (facies K) at their bases. The cross-bedding increase to medium scale (facies K) upwards. The cross-beds were deposited by migrating aeolian dunes. The size of the cross-beds may reflect the size of the dunes. The migrating dunes were occasionally interupted by flooding events as inferred by oscillation rippled sandstones of facies M. The flooding events may be the result of storm surges which flood the interdunal areas of the migrating dunes creating lakes or ponds (Hummel and Kocurek, 1984), or result from a slight rise in sea level in which a marine incursion attempts to transgress the dune field but can't, because the sand supply to the dune field is greater than the rise of sea level. As a result of the abundant sand supply, aeolian dunes reinitiate migration and are deposited over the marine reworked sandstones of facies M (Figure 28).

The tops of thicker aeolian dune sequences occasionally grade into contorted beds of facies L (Figure 28). The contortions are believed to have originated from the rapid trapment of air in the pores of the sand, followed by the pressured release of the air from overlying weight, causing the strata to contort. Overlying the contorted beds of facies L is oscillation rippled strata of facies M. Facies M occurs at the very top of the aeolian sequence and originates solely from marine transgression as evidenced by the deposition of overlying subtidal carbonates of facies H. Facies M in this situation represents marine reworking of the aeolian strata during a sea level rise or transgressive event.

Facies association 2 overlain by aeolian sandstone thus records the shallowing upward sedimentation of subtidal to intertidal to supratidal and finally terrestrial (aeolian) deposits in a protected lagoonal setting behind the Halfway barrier shoreline. The cyclic nature of facies association 2 is due to sea level flucuations. The peritidal shoreline is the most sensitive environment to sea level changes where even a slight change in water level will change the positioning of the subtidal, intertidal and supratidal zones. During longer stillstand periods, aeolian dunes are able to accumulate and migrate across the supratidal (sabkha) surfaces. Some of these sea level rises are recorded within dune deposits as oscillation rippled sandstones. The dunes continue to accumulate and migrate until they are finally transgressed during a higher sea level rise in which another cycle of deposition begins.

5.2.5 Lateral Facies Relationships of Aeolian Peritidal Sequences

In order for aeolian deposits to exist there are certain criteria that must be met. The accumulation of aeolian deposits are dependent upon the availability of a sand supply, sufficient wind energy to transport and rework the sand, and extended periods with suitable topographic and climatic conditions (Pye and Tsoar, 1990). Areas with these characteristics will be best suited for aeolian deposition while laterally adjacent areas lacking these properties will be bare of aeolian deposits.

In coastal settings, sand may be derived from several areas. The sand may be derived from marine sands which are made available by falling sea levels, from fluvial systems and deltas which transport the sand to the coastline or by an inland source in which the aeolian dunes migrate to the coastline. The Halfway sandstones are thick and would provide a large enough sand supply to the coast, but rose diagrams (Figure 16) of the aeolian sandstones indicate a seaward progradation pattern for the dunes. An onshore migration pattern would be expected if the sand source was from a marine source. As well, no fluvial or deltaic systems have been identified in the Halfway or Charlie Lake Formations. This leaves an inland source for the sand supply for the dunes. Sandy regolith of arid regions, which are unvegetated, may be reworked by winds to form aeolian dunes. The sand rich Kiskatinaw, Doig and Halfway Formations which would be subaerially exposed further east on the North American craton, would be an ideal source for wind reworking to form aeolian dunes. The location of the exposed regoliths would therefore control the location of the development of aeolian dunes. If the regolith is not exposed or not being weathered then there will be no source for the formation of aeolian dunes.

Sand that is entrained and transported by the wind is deposited and confined within topographic basins (Wilson, 1973). Aeolian deposits will continue to migrate within the basin until the sand reaches a pronounced break in the basin slope. Topographic highlands such as mountain ranges act as barriers to wind flow and deposition and accumulation will occur at the mountain base. If no such barriers exist, the dunes will continue to migrate in a dynamic state (Figure 30). Many grabens existed during Charlie Lake deposition and these grabens may have acted as depositional basins for the aeolian sands. The depth of the grabens are believed to have been very shallow therefore aeolian deposits accumulating within the grabens will have been thin, limited to the depth and size of the graben.

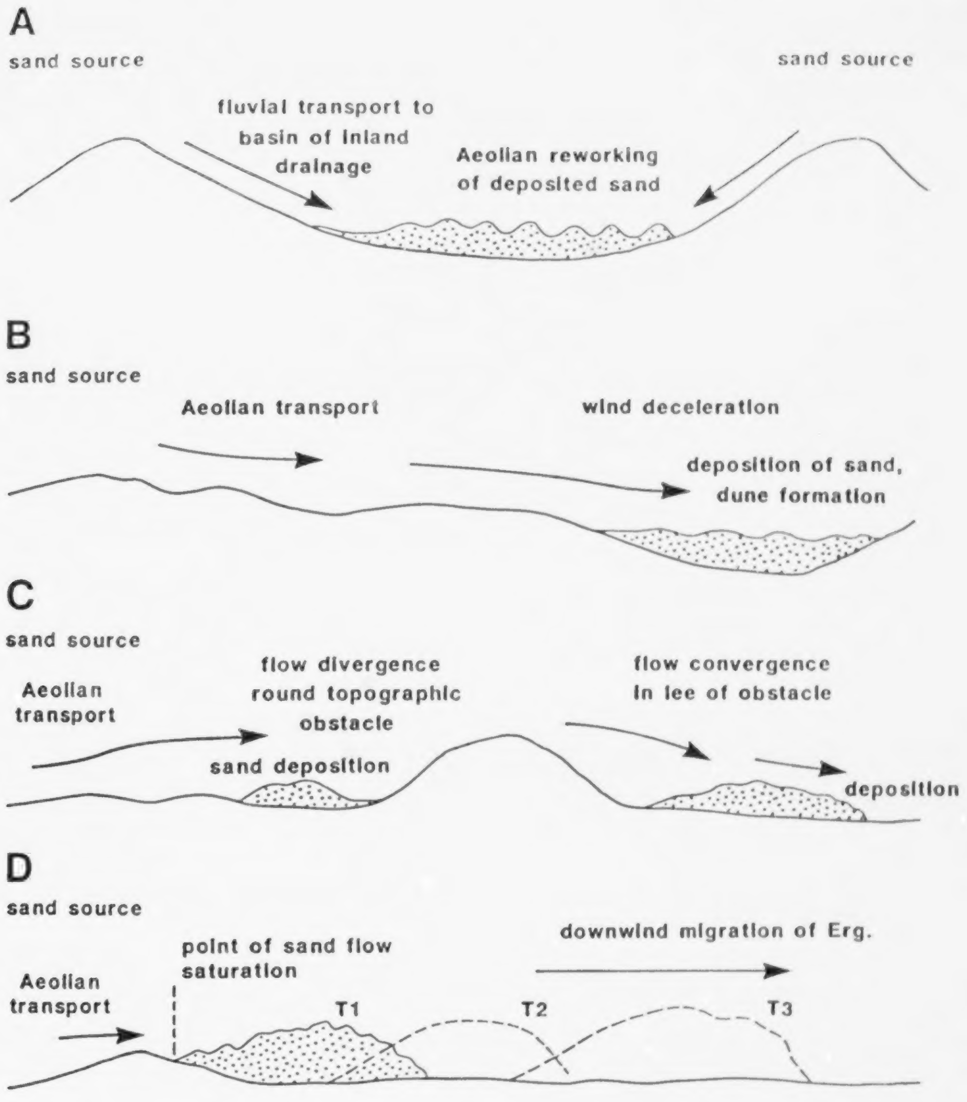

A
sand source
sand source
fluvial transport to basin of inland drainage
Aeolian reworking of deposited sand
B
sand source
Aeolian transport
wind deceleration
deposition of sand, dune formation
C
sand source
Aeolian transport
flow divergence round topographic obstacle
sand deposition
flow convergence in lee of obstacle
deposition
D
sand source
point of sand flow saturation
Aeolian transport
downwind migration of Erg.
T1
T2
T3

Figure 30. Schematic diagram showing topographic situations in which static (A - C) and dynamic (D) ergs may form (modified after, Pye and Tsoar, 1990)

Climate controls the extent of aeolian processes which occur in a region. Aeolian processes are more abundant in arid regions where vegetation cover and soil moisture are minimal (Marzolf, 1988). Wind regime is strongest on coastlines and in the latitudes of the trade wind belt and the mid-latitude westerlies, thus providing a greater potential for aeolian sand transport. The Charlie Lake peritidal shoreline is extremely long covering a depositional distance of 100's of km. Aeolian dunes would be dominant on this coastline where the exposed source regolith is being weathered and on the coastline within the trade wind belt. This does not mean that the coastlines in the equatorial zone or the mid-latitude zone above will not have aeolian deposition, just that the trade wind belt zone should have thicker and more frequent aeolian deposits. While aeolian deposition is occurring in the trade wind belt area, deflation or tidal processes will be occurring in the laterally adjacent wind zones.

If rates of sand supply are high and there is sufficient time to rework the sand, extensive fields of dunes and draas of an erg system will develop. However, the formation of thick, extensive aeolian deposits takes several thousands of years with little variation in climatic conditions. The sandstones of the Charlie Lake Formation are not thick (3m average) and this may be the result of the quick changes in sea level which do not allow sufficient time for development of thick, extensive aeolian deposits.

If the sand supply is sufficient, the wind strong enough for transport, long periods of climatic stability, and a topographic barrier or depression for accumulation exists, formation of large aeolian deposits or ergs may occur. Ergs consist of the migration of at least two of the largest aeolian bedforms called "draa's" (Wilson, 1973) or cover at least 20% of the migration surface (Kerr and Dott, 1988). Modern ergs such as the Algodones (Sweet et al., 1988) and Great Sand Dunes (Andrews, 1981) display zones of aeolian deposits. The central portion of the erg will contain many ripples, dunes, draas and interdunes (facies K) that upon migration will leave multiple cross-bedded sandstones. The margins of the erg contain only isolated dunes, sand sheets and interdunes which deposit single cross-bedded and low-angle to horizontal sandstones (Figure 31). Deflation and erosion occurs, producing scoured and coarse pavement in the areas outside of the erg margin. The multiple cross-bedded sandstones in the upper Charlie Lake Formation at Brown Hill represent deposition of the central erg while the single cross-bedded sandstone in the lower part of the outcrop section represent deposition of the marginal erg. If we could trace the upper sandstones downwind, marginal erg deposits should be found and if we trace the lower sandstones upwind, the central erg deposits should be found.

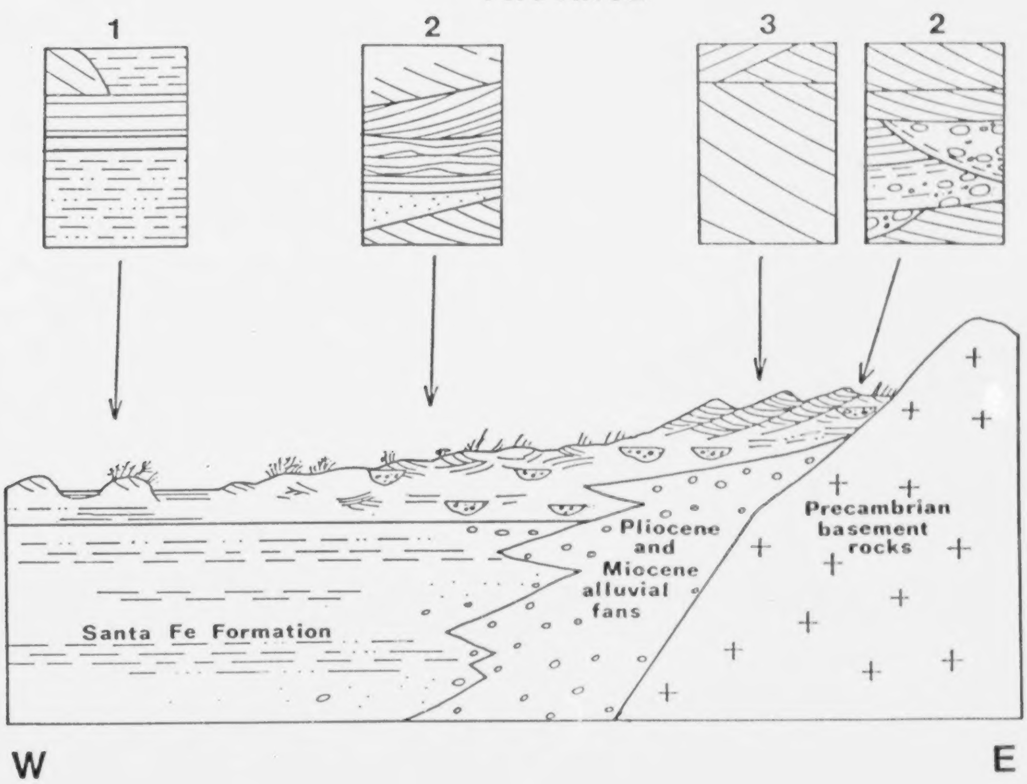

PROVINCE
1
2
3
2
Precambrian basement rocks
Pliocene and Miocene alluvial fans
Santa Fe Formation
W
E

Figure 31. Schematic cross-section showing depositional provinces (I, II, and III) of the Great Sand Dunes, Colorado. Province I consists of dune and lascustrine; province II consists of high and low-angle dune cross-bedding; and province III consists of high-angle dune cross-bedding (modified after, Andrews, 1981).

If the erg is transgressed again by a slow, low-energy marine incursion, the thinner marginal erg deposits will be completely marine reworked while only the tops of the thicker central erg deposits will be marine reworked (Figure 32). Thus, lateral to and overlying the single and multiple cross-bedded sandstones will be a massive or wave rippled sandstone (facies M). This produces a lateral succession from the central erg outward, of multiple cross-bedded sandstone, to single cross-bedded sandstone, to massive or wave rippled sandstone to supratidal deposits.

Facies Association 3: Shallow Water Shelf

Facies association 3 consists of only facies N. The facies is repeated forming a stacked succession of shallow shelf deposits. Facies N consists of storm deposits exibiting waning flow events. The facies is characteristic of the Baldonnel Formation and is significant because it represents deeper water carbonate deposition compared to the peritidal carbonates of the Charlie Lake Formation. Facies N probably represents the major transgression which ends deposition of Charlie Lake type deposits. These amalgamated carbonate shelf deposits may be the deeper water lateral equivalents of the peritidal deposits identified in the Sukunka-Bullmoose area to the south (Barss and Montandon, 1981).

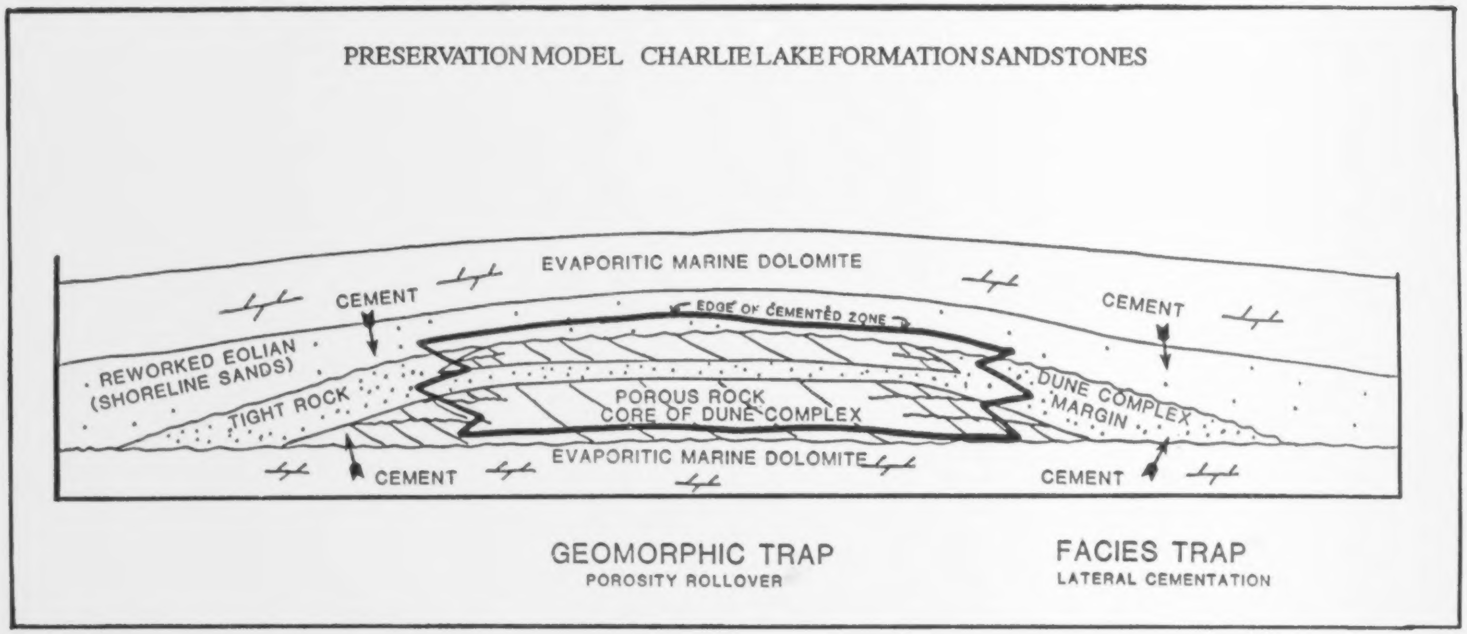

PRESERVATION MODEL CHARLIE LAKE FORMATION SANDSTONES
EVAPORITIC MARINE DOLOMITE
CEMENT
EDGE OF CEMENTED ZONE
CEMENT
REWORKED EOLIAN (SHORELINE SANDS)
TIGHT ROCK
POROUS ROCK CORE OF DUNE COMPLEX
DUNE COMPLEX MARGIN
EVAPORITIC MARINE DOLOMITE
CEMENT
CEMENT
GEOMORPHIC TRAP
POROSITY ROLLOVER
FACIES TRAP
LATERAL CEMENTATION

Figure 32. Preservation model for reservoirs in marine reworked aeolian sandstones of the Charlie Lake Formation after Fryberger's 1984 model in the Upper Minnesula sandstones. Margins of the erg are marine reworked while the central erg is preserved due to sand thickness and rate and force of marine transgression.

6.0.0 AEOLIAN DEPOSITIONAL ENVIRONMENTS

The nine sandstones of the Charlie Lake Formation at Brown Hill (Figure 19) are interpreted to be aeolian in origin. The interpretation is based on the fine sedimentary structures within the sandstones which resemble translatent, grainfall, and grainflow strata of Hunter (1977, 1981), Kocurek and Dott (1981) and Schenk (1983). There are many different types of aeolian systems (coastal and continental) and a varience of dune types within these systems (Breed and Crow, 1979; Fryberger et al., 1990). The nine aeolian sandstones of the Brown Hill section have common sedimentary features but also many differences, inferring a changing aeolian environment during deposition of these sandstones.

6.1.0 Depositional Setting

Aeolian (erg) deposits that intertongue with marine deposits are interpreted as being deposited in a marine or coastal setting (Chan and Kocurek, 1988). As cited in chapter 5, there are many ancient examples of aeolian and marine facies interbedding. In marine settings, eustatic sea level changes produce abrupt facies transitions on the margin of an erg. The thickness and type of erg deposits depends upon the rate of sand supply to the erg, dune organization, and duration of lowstand (Porter, 1986). The coastal dunes are commonly transgressed and capped by marine deposits. In non-marine settings, the erg margins are interfingered with fluvial sandstones and mudstones (Middleton and Blakey, 1983) and volcanic deposits (Porter, 1986). Dune facies are capped or transgressed by fluvial and lacustrine deposits during basin subsidence. The interbedding of aeolian and peritidal deposits observed in the Charlie Lake Formation indicates that the aeolian dunes were deposited in a coastal setting. This implies that the dunes prograded over the supratidal flats during conditions favourable for aeolian processes.

6.2.0 Aeolian Dune Types

The Charlie Lake Formation sandstones vary in amount of cross-bed sets with the lower sandstones in the Brown Hill section containing single cross-beds and the upper sandstones containing multiple cross-beds (Figure 19). The high-angle cross-beds represent deposition by migrating aeolian dunes. There are many kinds of aeolian dunes (Figure 33) such as blowout, barchan, parabolic, barchanoid ridge, dome, transverse, reversing, linear and star dunes to name a few (McKee, 1979). Each dune type has characteristic internal stratification structures due to the differences in dune formation and migration pattern (Pye and Tsoar, 1990).

Several approaches can be used to determine the dune types preserved in sandstones. The set geometry of a deposit can be used to determine the dune type (McKee, 1966; Kocurek,

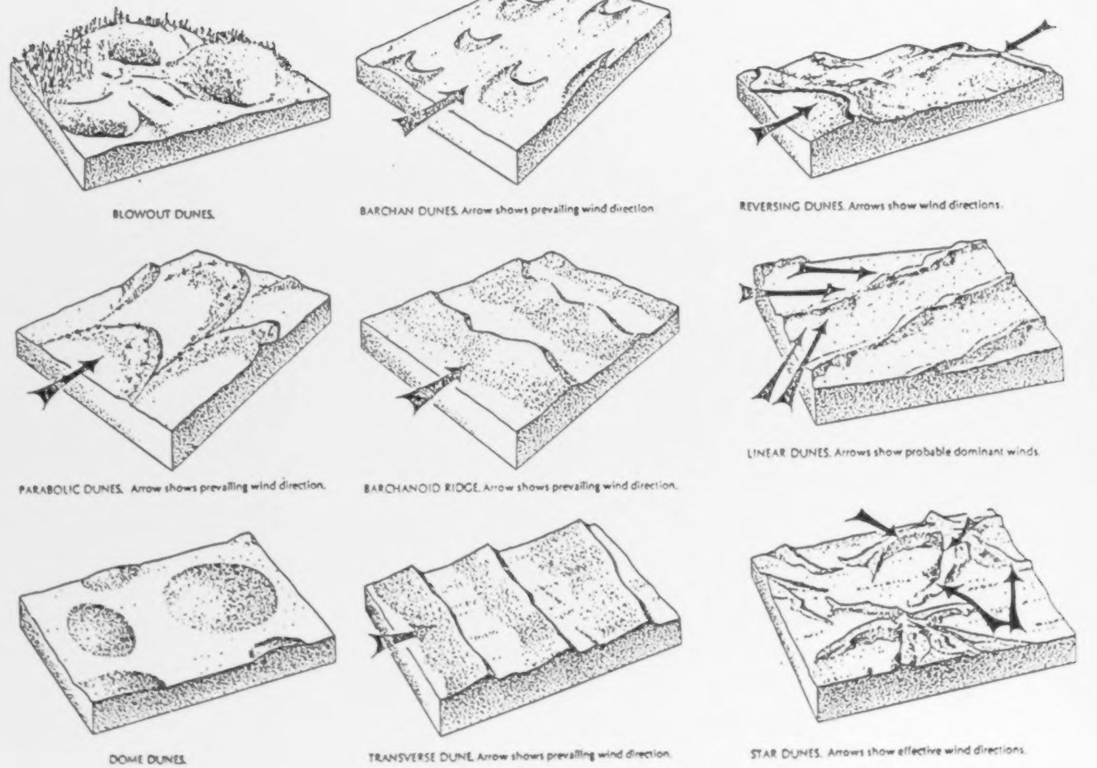

BLOWOUT DUNES.
BARCHAN DUNES. Arrow shows prevailing wind direction
REVERSING DUNES. Arrows show wind directions.
PARABOLIC DUNES. Arrow shows prevailing wind direction.
BARCHANOID RIDGE. Arrow shows prevailing wind direction.
LINEAR DUNES. Arrows show probable dominant winds.
DOME DUNES.
TRANSVERSE DUNE. Arrow shows prevailing wind direction.
STAR DUNES. Arrows show effective wind directions.

Figure 33. Dune forms produced by unidirectional and multiple directional wind regimes. Parabolic, barchan, barchanoid, and transverse dune forms are produced in unidirectional wind regimes. Linear and reversing dune forms are produced in bidirectional wind regimes. Star dunes form in complex wind regimes. Dome dunes are embryonic forms of other dunes while blowout dunes are parabolic dunes without arms (modified after McKee, 1979).

1981; Rubin and Hunter, 1983). Another approach invokes the use of foreset dip angles and dip-direction dispersion patterns (Glennie, 1970; McKee, 1979; Ahlbrandt and Fryberger, 1980, 1982). The distribution and proportion of aeolian stratification types in foresets is another approach which infers dune type and dune orientation with respect to wind regime (Kocurek and Dott, 1981; Kocurek, 1986). If possible, all three methods should be used to infer dune type. However, due to the poor quality of some sandstone exposures and the thin lateral extent (20m) of the outcrop at the Brown Hill section, only the stratification types and their distributions, along with the limited use of set geometry, will be used to interpret the dune types of the Charlie Lake Formation.

The three types of aeolian stratification show a characteristic and consistent distribution on modern dunes, and as a result, the understanding of their formation on various dunes can be used to interpret ancient aeolian sandstones based on these modern patterns and associations (Kocurek and Dott, 1981). There are two common variations of stratification types and their distribution within the high-angle cross-beds of the Charlie Lake sandstones. In the thicker sandstones (Figures 19 and 34), the lower cross-beds dominantly consist of sandflow strata with minor translatent strata and very little grainfall strata. The upper cross-beds are dominantly composed of translatent and grainfall strata with minor sandflow strata. The thinner Charlie Lake sandstones are sedimentologically similar to the lower cross-beds of the thicker sandstones (Figure 35).

The cross-beds of the thin sandstones and the lower parts of the thicker sandstones form small scale cross-beds. The ratio of wind ripple: grainfall: sandflow for these cross-beds is 2:0:8. The cross-beds are dominated by sandflow strata which is produced by avalanching sand down slipfaces of dunes. Aeolian dunes which produce abundant sandflow deposits include crescentic (barchan, barchanoid ridge, transverse), linear (longitudinal), and star morphologies. The orientation of the cross-strata continuously dip in the same direction suggesting deposition by unidirectional winds leaving a crescentic (barchan, barchanoid ridge and transverse) morphology as the probable dune form since linear (longitudinal) and star dunes are produced by multidirectional winds (Figure 36). The wedge shaped toes of the sandflow strata are interbedded with wind ripple laminations (Plate 19) and may be due to lee slope eddies reworking the sandflow deposits, or ripples migrating onto the sandflow strata aprons. Plinths of dunes that produce abundant wind ripple laminae are best developed where the interactions of the dune and the primary wind cause a secondary airflow that results in transport along the lee face (Kocurek, 1986). The along-slope secondary airflow develops where the dune crestline is not normal to the primary wind which is typical for linear dunes (Tsoar, 1983; Rubin and Hunter, 1985), star dunes (Kocurek, 1986) and crescentic dunes that are oblique to the wind (Rubin and Hunter,

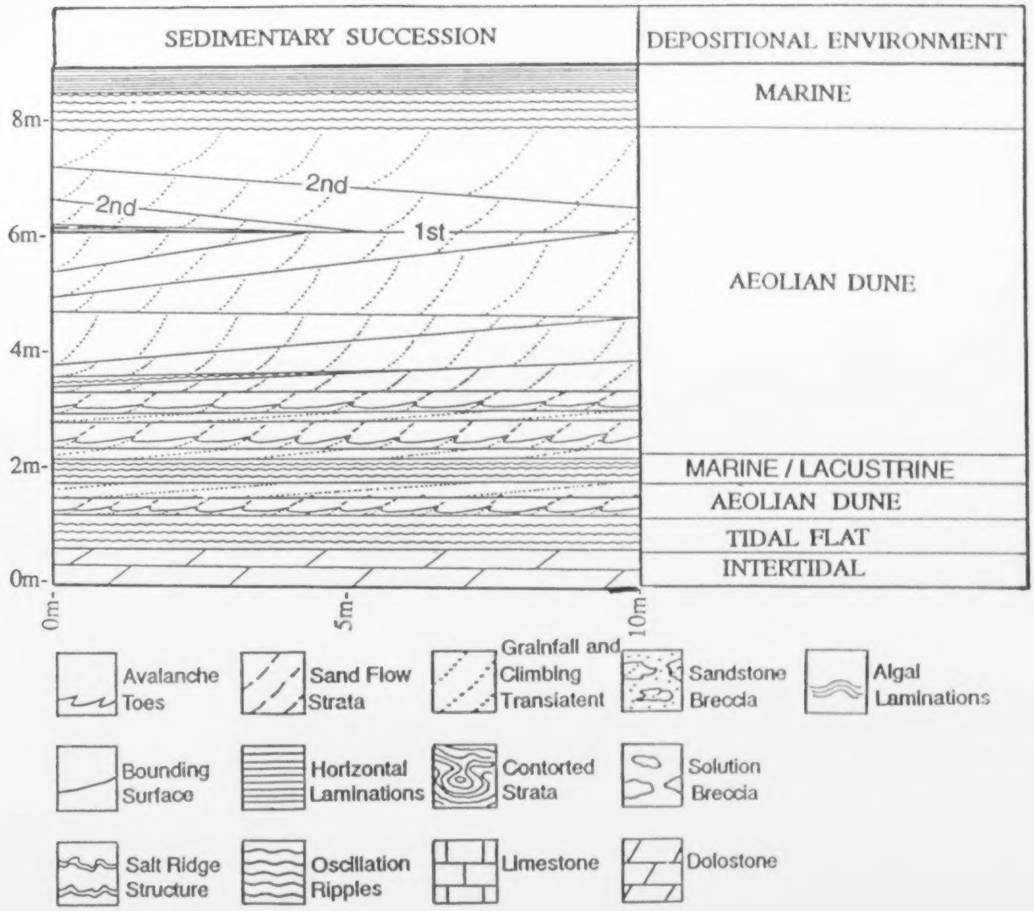

SEDIMENTARY SUCCESSION
DEPOSITIONAL ENVIRONMENT
MARINE
AEOLIAN DUNE
MARINE / LACUSTRINE
AEOLIAN DUNE
TIDAL FLAT
INTERTIDAL
8m-
6m-
4m-
2m-
0m-
2nd
2nd
1st
0m-
5m-
10m
Avalanche Toes
Sand Flow Strata
Grainfall and Climbing Translatent
Sandstone Breccia
Algal Laminations
Bounding Surface
Horizontal Laminations
Contorted Strata
Solution Breccia
Salt Ridge Structure
Oscillation Ripples
Limestone
Dolostone

Figure 34. Detailed schematic diagram showing the sedimentary structures, internal stratification styles and bounding surface hierarchy of the eighth aeolian sandstone at the Brown Hill section.

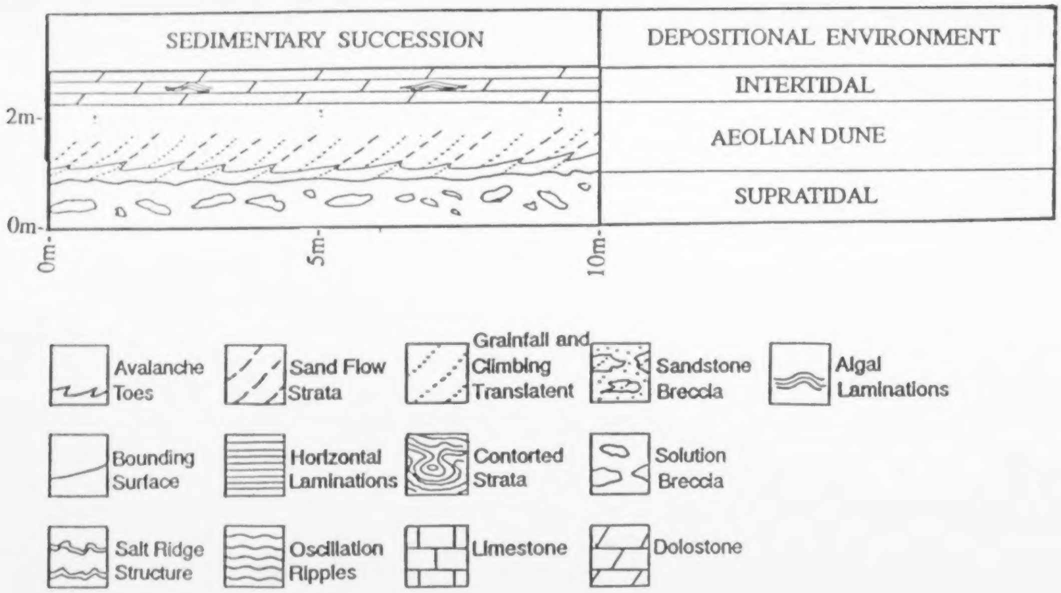

SEDIMENTARY SUCCESSION
DEPOSITIONAL ENVIRONMENT
INTERTIDAL
AEOLIAN DUNE
SUPRATIDAL
2m-
0m-
0m-
5m-
10m-
Avalanche Toes
Sand Flow Strata
Grainfall and Climbing Translatent
Sandstone Breccia
Algal Laminations
Bounding Surface
Horizontal Laminations
Contorted Strata
Solution Breccia
Salt Ridge Structure
Oscillation Ripples
Limestone
Dolostone

Figure 35. Detailed schematic diagram showing the sedimentary structures and internal stratification styles of the second aeolian sandstone at the Brown Hill section.

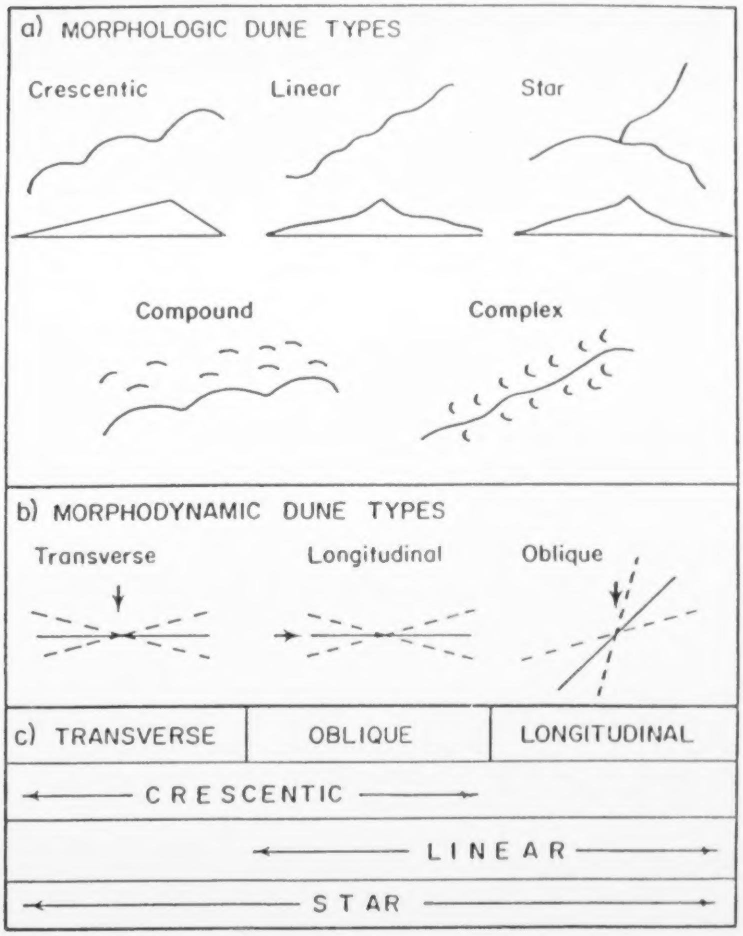
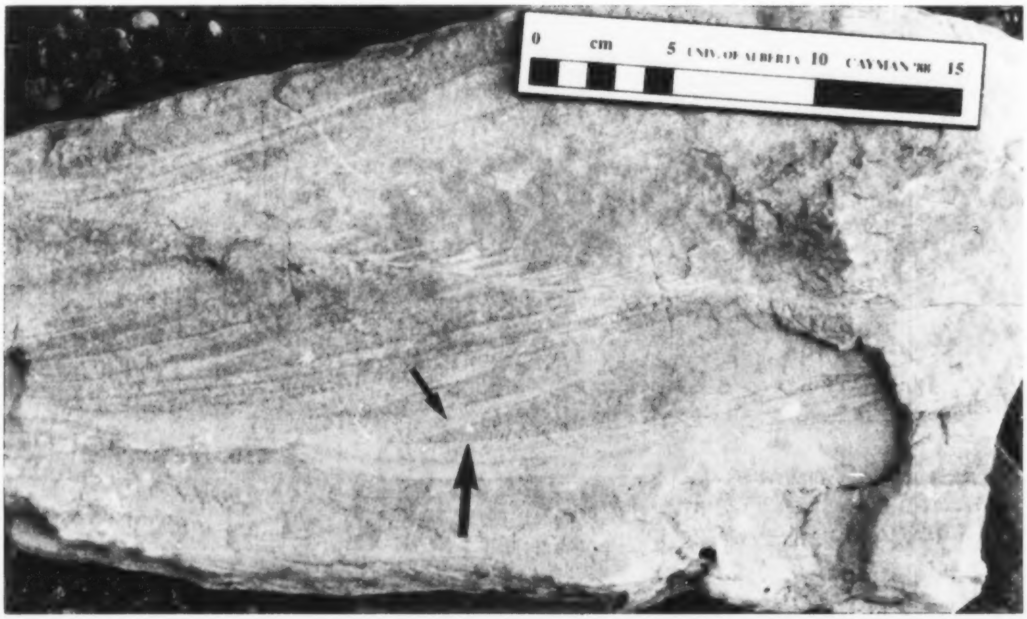

a) MORPHOLOGIC DUNE TYPES
Crescentic
Linear
Star
Compound
Complex
b) MORPHODYNAMIC DUNE TYPES
Transverse
Longitudinal
Oblique
c) TRANSVERSE
OBLIQUE
LONGITUDINAL
CRESCENTIC
LINEAR
STAR

Figure 36. Classification of dunes. (a) Simple dunes, illustrating plan view of crestline form and cross-sectional view; lower illustrations are plan view of draas. (b) Arrow shows long term wind vector with respect to orientation of dune crestline (15 degrees by dashed lines). (c) Range of orientations for simple dunes (modified after Kocurek, 1991).


0
cm
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CAYMAN '88
15

Plate 19. Stratification configuration of high-angle cross-beds of facies K within the eighth aeolian sandstone of the Brown Hill section. The large arrow is pointing to avalanche toes of grainflow origin and the small arrow is pointing to wind ripple laminations. Scale bar for scale.

1983). The interbedded configuration (Plate 19) of the sedimentary structures are indicative of an oblique orientation (Kocurek, 1991) (compare Plate 19 to strata in Figure 37). The lower cross-beds represent crescentic dunes that are moving at a slight oblique angle to the mean wind direction (Figure 38).

The upper cross-beds of the thicker sandstones form medium scale cross-beds. The ratio of wind ripple: grainfall: sandflow for these cross-beds is 7:1:2. The cross-beds are dominated by wind ripple strata and display a rarity of grainfall and sandflow cross-strata. The rarity of grainfall and sandflow strata indicates that either slipface avalanching is not an important process, or it is not preserved within this dune type. The strata within the cross-bed sets dip in the same direction suggesting transport by unidirectional winds. Cross strata consisting only of wind-ripple laminae may represent a dune type or portion of a dune marked by an absence of a slipface and characterized by alongslope transport which is low-angle oblique or longitudnal (Kocurek, 1991). Most of the surfaces of linear (longitudnal) dunes are covered by wind ripple deposits with only the upper 10% of the dune height resricted to slipface deposits (Kocurek, 1986). Only the lower wind rippled plinth portions of such dunes would be preserved after the migration and stacking due to dune climbing. Linear dunes that are migrating obliquely will deposit unidirectional cross-beds as shown by Rubin and Hunter (1985). However, the lack of sets of low-angle wind-ripple strata, which are typical of oblique and longitudinal dunes, would suggest formation by a more transverse bedform. The upper cross-beds best represent transverse dunes that are moving at an oblique angle to the mean wind direction which unlike the lower cross-beds do not have well developed or preserved slipfaces (Figure 39).

Modern ergs are characterized by rhythmically spaced dunes and interdunes. The dunes may be simple (without smaller dunes superimposed), compound (dunes with similar dunes superimposed) or complex (dunes with different types superimposed) (Figure 36). The migration of the dunes produces an internal hierarchy of bounding surfaces (Figure 40). Three orders of bounding surfaces have been identified in ancient aeolian deposits (Brookfield, 1977; Kocurek, 1981). In addition, a major diastem surface called a "supersurface" has also been interpreted within some deposits (Kocurek, 1988). First-order surfaces are flat lying, regionally extensive, and cross-cut all others except for supersurfaces. Interdune deposits are commonly associated with first-order bounding surfaces (Kocurek, 1981). Second-order surfaces dip in a downwind direction, lie between first-order surfaces and are formed by the migration of dunes on the backs of draas. Third-order surfaces bound bundles of foresets within a set of cross-strata and are formed as reactivation surfaces during changing wind directions. Supersurfaces represent the truncation of ergs or a hiatus due to changing conditions and external events. Bounding

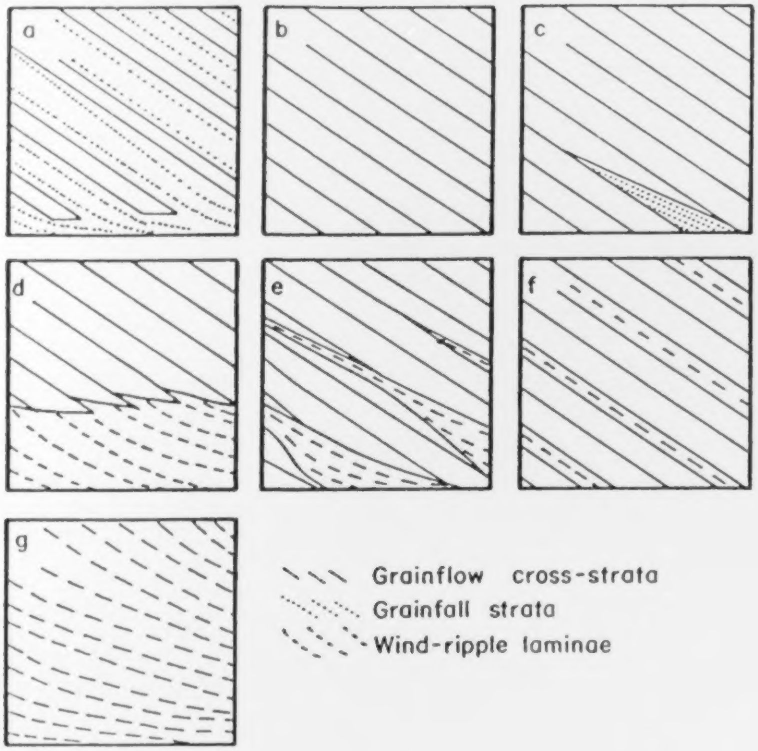


Figure 37. Common stratification configurations for aeolian bed sets. Figures a-c are indicative of transverse configurations due to grainflow dominant strata. Figure 37a is characteristic of a smaller dune or produced by higher winds than 37b since grainfall deposits reach the base of the slipface. Figure 37c represents a transverse dune form with a storm event in which high winds deposited grainfall strata at the base of the slipface. In figure 37d, avalanching and wind-ripple migration occurred simultaneously indicating a secondary lee-face wind common to oblique dune configurations. Figure 37e strata are produced by cyclic winds in which periods of transverse winds cause slipface advance by grainflow and periods of oblique or reversed winds causing lee-face modification accompanying alongslope transport. Figure 37f infers cyclic winds as in 37e but without any significant change in dune shape. Figure 37g may represent a dune without a slipface and characterized by alongslope transport (low-angle oblique or longitudnal) or represent a low-relief transverse or oblique orientation (modified after Kocurek, 1991).

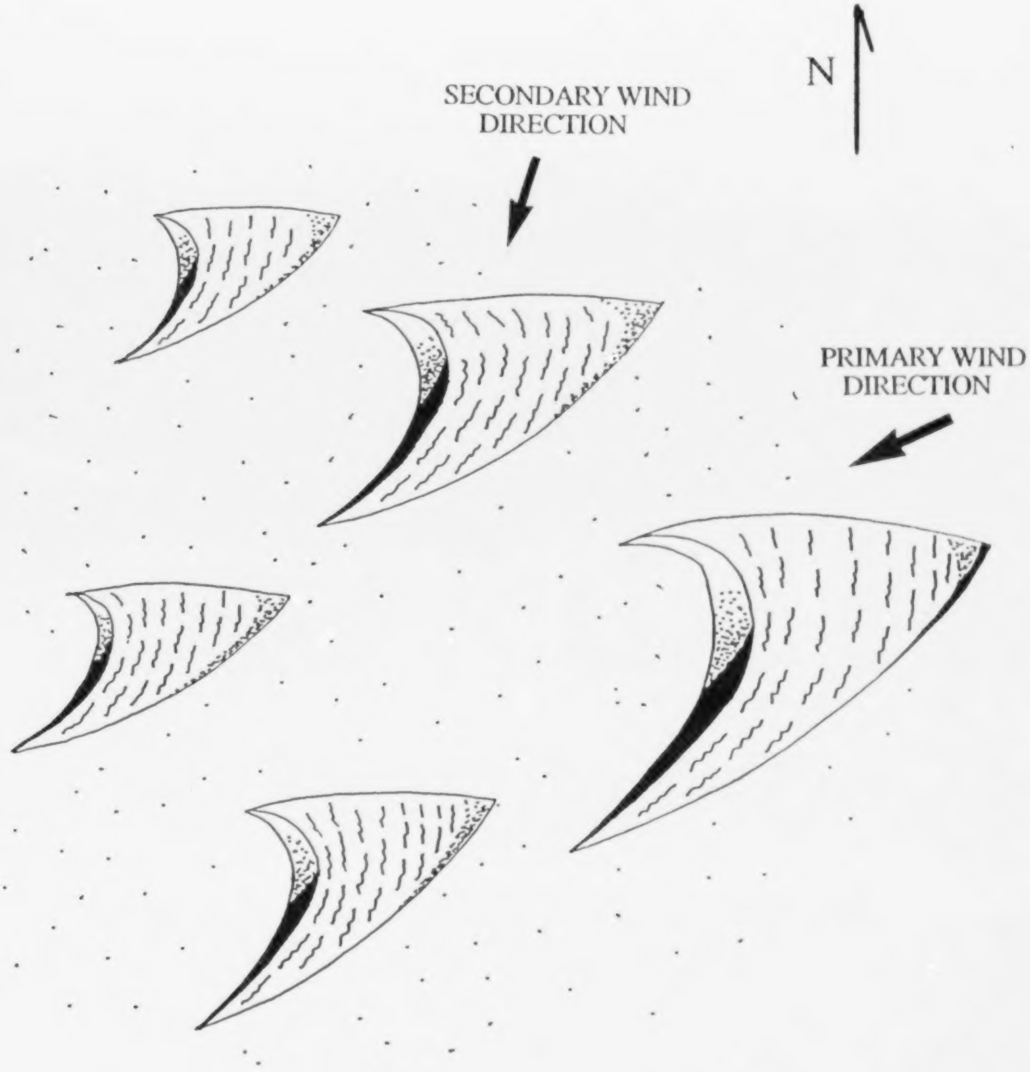

N
SECONDARY WIND DIRECTION
PRIMARY WIND DIRECTION

Figure 38. Obliquely migrating crescentic (barchan) dune forms interpreted for the dunes that produced the lower cross-beds in the thicker sandstones and the cross-beds in the thin sandstones of the Charlie Lake Formation at the Brown Hill section.

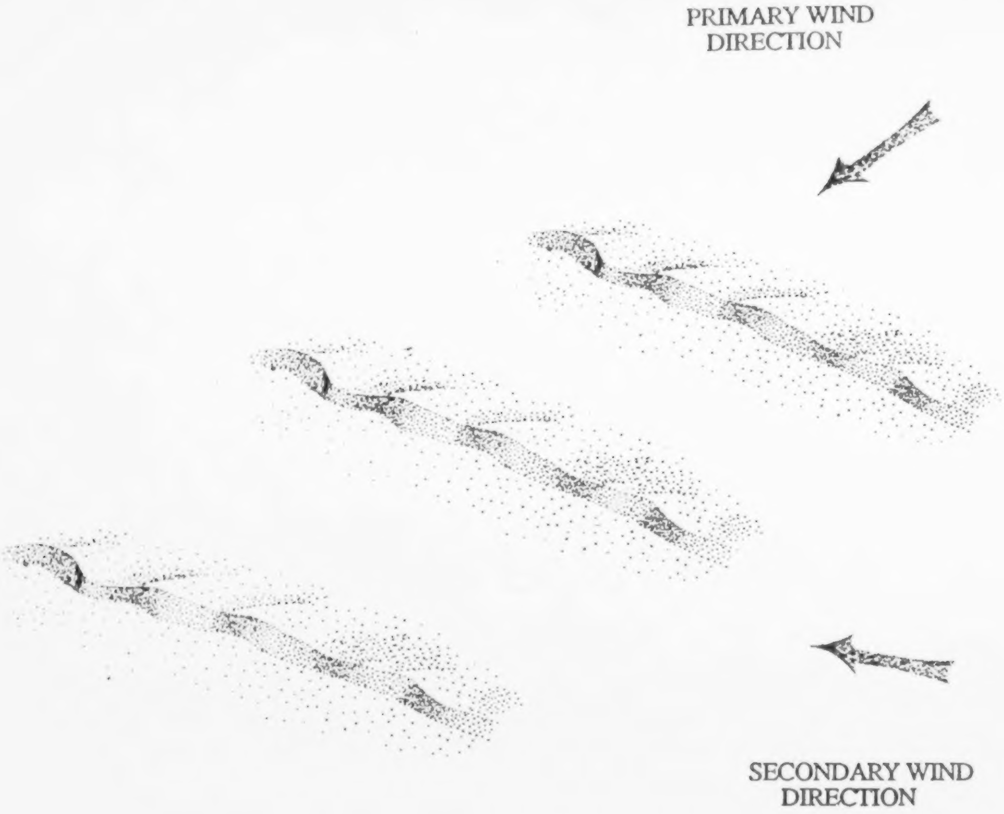

PRIMARY WIND DIRECTION
SECONDARY WIND DIRECTION

Figure 39. Obliquely orientated transverse dune forms interpreted for the dunes that produced the upper cross-beds in the thicker sandstones of the Charlie Lake Formation at the Brown Hill section (modified after McKee, 1979).

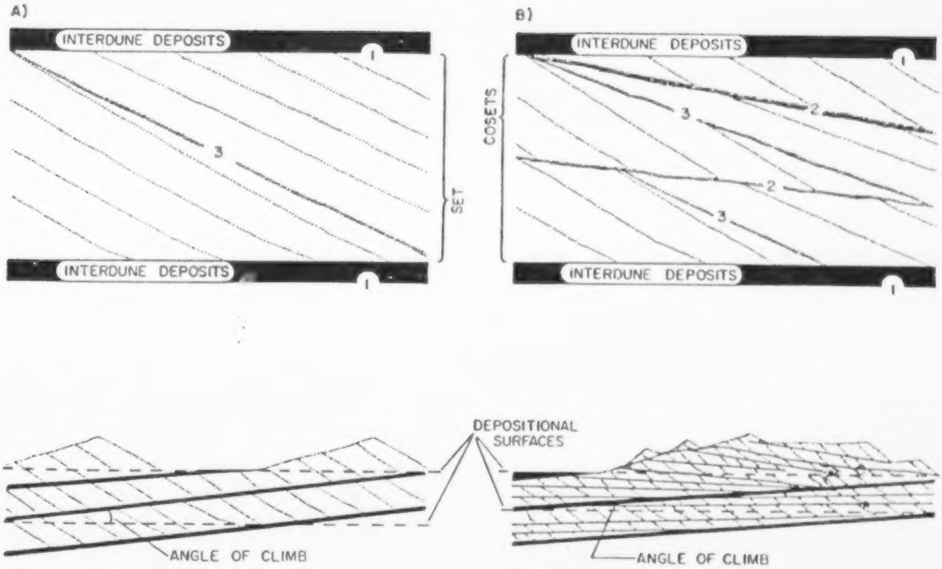

A)
INTERDUNE DEPOSITS
1
3
INTERDUNE DEPOSITS
1
SET
B)
INTERDUNE DEPOSITS
1
COSETS
3
2
2
3
INTERDUNE DEPOSITS
1
DEPOSITIONAL SURFACES
ANGLE OF CLIMB
ANGLE OF CLIMB

Figure 40. Model for the formation of first-order bounding surfaces with the migration of simple dunes and interdune areas (A), and the migration of draas and interdune areas (B). First-, second-, and third-order bounding surfaces are indicated by 1, 2, and 3, respectively (modified after Kocurek, 1988).

surfaces produced by migrating simple dunes consist of only first and third order surfaces while migrating compound and complex dunes produce first, second and third order bounding surfaces (Kocurek, 1988).

The nine sandstones of the Brown Hill section (Figure 19) have been labeled first, second, third and so on in ascending order. The first, second, third, fourth, and fifth, sandstones consist of one cross-bed set without interdune deposits and bounding surfaces and are interpreted as migrating simple dunes. The seventh sandstone consists of three cross-bed sets which are separated by thin interdune deposits (Figure 41). This sandstone lacks second order surfaces and is interpreted as the migration of simple dunes. The sixth and ninth (Figure 42) sandstones have single or multiple cross-beds (two or three) between thick interdune deposits. Again there are no second order bounding surfaces and these sandstones are interpreted as deposits of migrating simple dunes.

The only sandstone that displays second order bounding surfaces is the eighth sandstone; it is interpreted as a deposit from the migration of a draa with superimposed dunes. The sandstone displays two first order bounding surfaces with numerous second order bounding surfaces (Figure 34). First order surfaces are produced by the larger draa and the second order surfaces are produced by the superimposed dunes. The stratification styles of the strata within the first and second order surfaces are identical suggesting the superimposed dunes are of the same type.

The shape of the bounding surfaces can also be used to infer dune morphology. Cross-beds with undulatory bounding surfaces are typical of crescentic dune forms while cross-beds with planar surfaces are typical of straight crested dunes (Kerr and Dott, 1988). Undulatory surfaces are common in the lower cross-beds while planar surfaces are common in the upper cross-beds. The upper and lower bounding surface geometry is consistent with the interpretation provided by the stratification styles.

The stratification styles and the bounding surface hierarchy display two dune systems. The first dune type occurs in the lower, thinner sandstones and at the bases of the upper thicker sandstones. These sandstones are interpreted to be simple migrating small crescentic dunes probably of barchan morphology. The second dune type occurs in the upper part of the thicker sandstones and are interpreted as simple migrating oblique transverse dunes. In one occasion (eighth sandstone) migration of superimposed dunes of the same kind (oblique linear) form compound erg deposits.

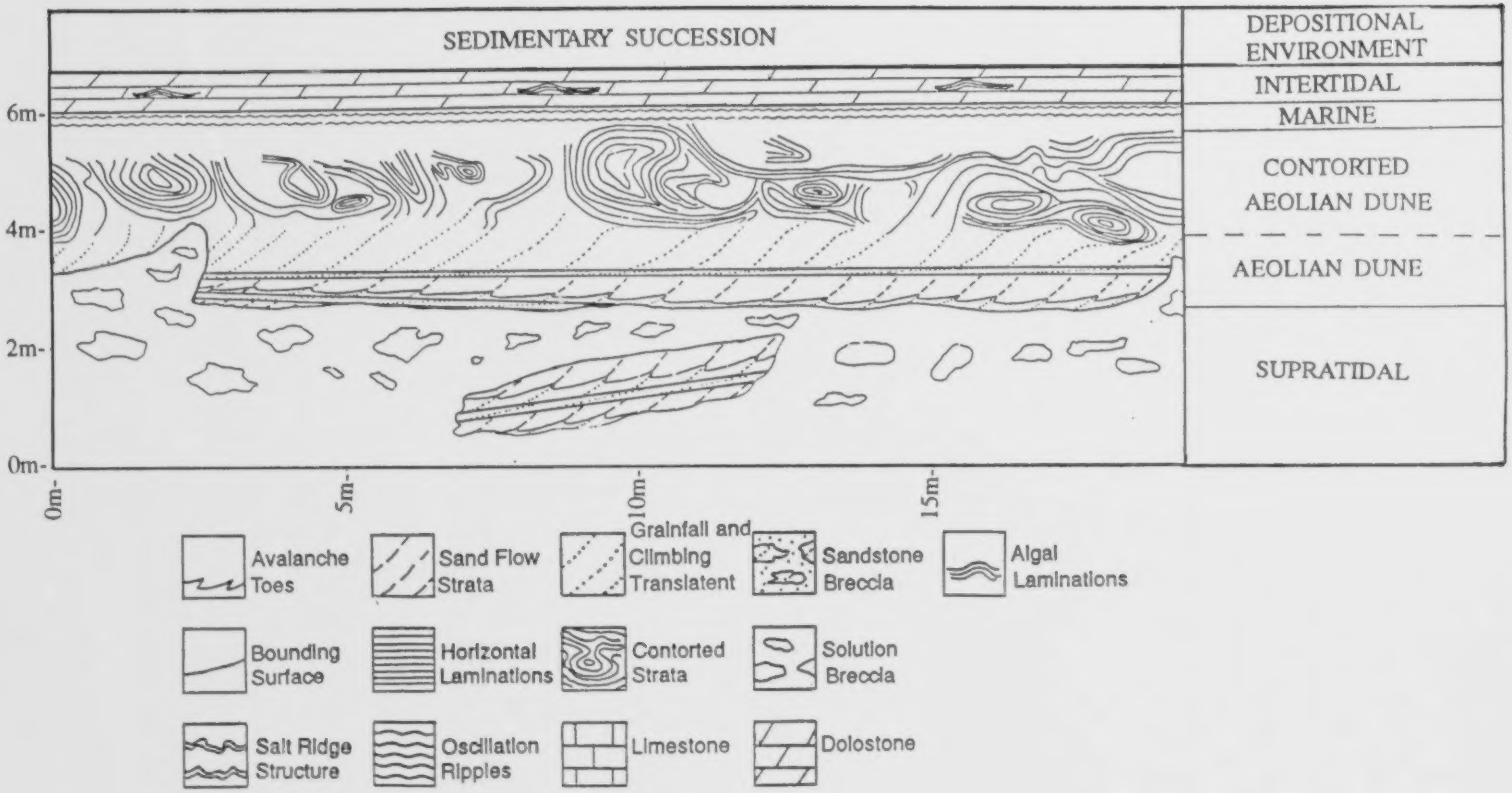

SEDIMENTARY SUCCESSION
DEPOSITIONAL ENVIRONMENT
INTERTIDAL
MARINE
CONTORTED AEOLIAN DUNE
AEOLIAN DUNE
SUPRATIDAL
6m-
4m-
2m-
0m-
0m-
5m-
10m-
15m-
Avalanche Toes
Sand Flow Strata
Grainfall and Climbing Translatent
Sandstone Breccia
Algal Laminations
Bounding Surface
Horizontal Laminations
Contorted Strata
Solution Breccia
Salt Ridge Structure
Oscillation Ripples
Limestone
Dolostone

Figure 41. Schematic diagram showing the sedimentary structures, internal stratification styles and bounding surface hierarchy of the seventh aeolian sandstone at the Brown Hill section.

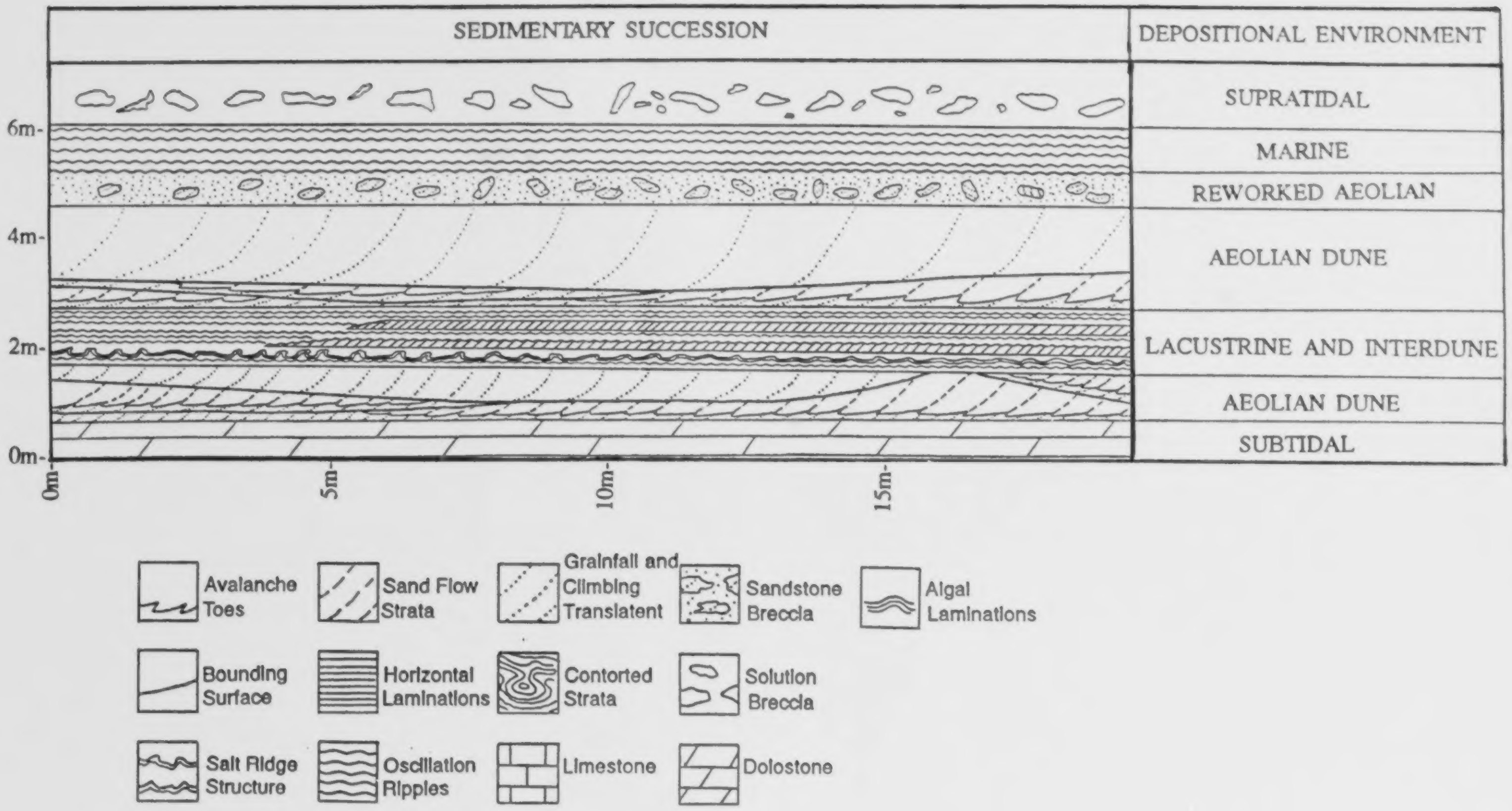

SEDIMENTARY SUCCESSION
DEPOSITIONAL ENVIRONMENT
SUPRATIDAL
MARINE
REWORKED AEOLIAN
AEOLIAN DUNE
LACUSTRINE AND INTERDUNE
AEOLIAN DUNE
SUBTIDAL
6m-
4m-
2m-
0m-
0m-
5m-
10m-
15m-
Avalanche Toes
Sand Flow Strata
Grainfall and Climbing Translatent
Sandstone Breccia
Algal Laminations
Bounding Surface
Horizontal Laminations
Contorted Strata
Solution Breccia
Salt Ridge Structure
Oscillation Ripples
Limestone
Dolostone

Figure 42. Detailed schematic diagram showing the sedimentary structures, internal stratification styles and bounding surface hierarchy of the ninth aeolian sandstone at the Brown Hill section.

6.3.0 Interdune Deposits

An interdune is a geomorphic area enclosed or partially bounded by dunes or other aeolian deposits such as sand sheets (Ahlbrandt and Fryberger, 1981). Interdunes differ greatly in size and shape depending upon the types of dunes that are separating them. Interdunes are divided into erosional or deflationary, dry, damp, wet or evaporitic based on the moisture content during sedimentation. In some instances, several different interdune types occur together to form a wetting or drying upward succession (Kocurek, 1981). The thickness and lateral dimensions of the interdune deposits can also be used to suggest dune morphology.

Deflationary interdunes are usually void or consist of coarser granule size lags. The lack of deposition is due to the sediment being removed by wind processes or the bypassing of sediment over the interdune surface. The coarser grains are too large to be removed by wind and are left behind as a lag deposit. Most of the Charlie Lake interdunes are void of sediment and are thus classed as the non-deposition deflationary type. Less commonly the sandstones have lag deposits along the interdune surfaces as shown in the eighth sandstone (Figure 34). Deflationary interdunes are common to barchan dunes due to their morphological origin. Barchans tend to form in areas where the sand supply is minimal therefore the sand in this part of the aeolian chain is trapped, accumulated and transported within the dunes leaving the interdune areas void of sediment.

Dry depositional interdunes are the most common in modern and ancient aeolian deposits. Dry interdunes are usually poorly sorted and consist of wind ripple produced strata, curved or irregular surfaces of erosion, bioturbation by plants and insects, grainfall strata, granule ripples, and thin deposits produced by small dune forms that migrate rapidly across the interdune. The horizontal wind ripple laminations seen above bounding surfaces are of this type. The horizontal laminations are produced by wind ripples migrating across the interdune floor. The wind ripples are preserved by the overlying migrating dune. The thickness of the interdune deposit is dependent upon the length of time it takes the dune to migrate over it. Rapid dune migration leaves interdune deposits that are thin while slow dune migration allows thick interdune accumulation to occur. A few of the Charlie Lake sandstone interdunes consist of 5-10cm thick horizontal to slightly low angle laminations which separate the tabular and wedge-planar cross-beds. The horizontal laminations are produced by the migration of wind ripples across the interdune floor.

Damp interdunes are usually a transitional phase between wet to dry interdune facies. During periods of ephemeral moisture, the sand becomes damp and cohesive. Sand blowing across the damp surface frequently adhere to the surface producing adhesion ripples and/or adhesion warts (Kocurek and Fielder, 1982). Adhesion ripples form as tiny, subparallel ridges that climb into the wind. No damp interdune deposits were recognized in the Charlie Lake sandstones at Brown Hill.

Wet depositional interdunes are sediments depositied in bodies of standing water within and between the various dune forms. These bodies of standing water are in the form of lakes and ponds and become flooded by high perennial water tables, fluvial systems (Langford and Chan, 1989), rain storms, or marine storm surges (Hummel and Kocurek, 1984). Sedimentary features associated with wet interdunes include trapped clays and silt, bioturbation, contortions caused by over-riding migrating dunes (Hunter, 1981), increased cementation, and subaqueous sandstone structures such as wave ripples (Ruegg, 1983; Hummel and Kocurek, 1984).

The only sedimentary feature related to wet interdune deposition in the Charlie Lake sandstones at the Brown Hill section are 10cm to 1.5m thick symmetrical rippled sandstones (facies M) interbedded between high angle aeolian dune cross-beds (facies K) (Figures 34 and 41). At Padre Island, Texas, the dune fields are periodically flooded by seasonal storm surges. The waters from the surge, flood the interdune areas creating lakes and ponds, however the stronger surges may destroy smaller dunes with only the larger oblique dunes remaining emergent (Hummel and Kocurek, 1984). The wet interdune deposits would only be expected to be as wide as the interdune area associated with the dune type. For example, lakes or ponds between the interpreted barchan dunes of the Charlie Lake sandstones should not be extensively laterally continuous as the interdune areas of barchan dunes are not very wide. The wet association would pinch out laterally into damp and dry interdune associations (Figure 34).

The symmetrical rippled sandstones between dune cross-beds only occur in the thicker Charlie Lake aeolian deposits (sandstones six, eight and nine). In the ninth sandstone (Figure 42), a symmetrical rippled bed grades laterally into and over several 5cm thick high angle cross-bedded units. The cross-beds are of aeolian origin and may represent a period of deposition when the erg was undersaturated with sand. Due to low sand supply, aggradation of the erg surface was limited to the rate of subsidence and water table rise. The capillary rise of groundwater into the basal portions of the dune prevents deflation of the sedimentary structures produced by the migrating dunes thus preserving thin deposits of the dunes (Loope and Simpson, 1992). However, the symmetrical rippled upper surface of the thin dune deposits suggests the dunes were flooded or transgressed by the thick laterally adjacent water body. The erg sediment supply was sufficient for a short period of time to compensate for the sea-level rise but eventually was flooded by the marine incursion. The sand supply rate or the rate of sea-level rise fluctuated periodically to produce a mixed sequence of thin aeolian cross-beds and wave rippled sandstone (Plate 20 and Figure 42).

In the coastal erg facies of the Entrada Sandstone, interdune deposits do not exist, but the dune cross-beds are interbedded with marine deposits which are similar to interdune deposits of the central erg facies (Kocurek, 1981). The development of dunes and interdune areas may have been inhibited by periodic marine flooding. The wave rippled facies in the sixth, eighth and ninth sandstones therefore may not be lacustrine interdune deposits but deposits of aeolian sands which were reworked by marine incursions during slight rises in sea-level.

The lateral extent and thickness of interdune deposits are commonly dependent upon dune type. The greater the sinuosity of the dune, the greater the discontinuity of the interdune deposits. Migrating barchan dunes and their associated interdunes would deposit discontinuous interdune deposits between cross-beds while interdune deposits of transverse dunes tend to be more continuous over great distances. The thickness of interdune sediments are dependent upon the rate of migration of adjacent dunes. Interdune deposits are thinnest in dunefields with rapidly moving dunes, but are thicker among slow moving or immobile types such as linear and star dunes. Linear and star dunes tend to aggrade vertically, so the interdune deposits are thick, whereas the usually rapid migrating barchan dunes and transverse dunes usually have thin interdune deposits. The very thin or lacking interdune deposits of the Charlie Lake sandstones suggest rapid migration of dunes which is commonly associated with barchan dunes. The thickness of the interdunes coincides with the interpretation of dune morphology based on stratification types and styles. The lateral limits of the interdunes can not be determined as the outcrop is only 20m wide.

6.4.0 Erg Migration

Modern sand seas such as the Namib, Great Sand Dunes, White Sands, Guerrero Negro, and the Algodones dune fields have been extensively studied in the field and by Landsat imagery. Comparison of the various dune fields reveal some similarities in dune migration patterns and positioning of the dune morphologies in the field.

The dune fields consist of a main sand body or erg made of large dunes and an erg margin characterized by small isolated dunes and aeolian sand sheets. Dunes of the main erg portion generally consist of compound and complex linear and/or crescentic forms. The compond/complex linear dunes have star, dome or barchan dunes superimposed upon them

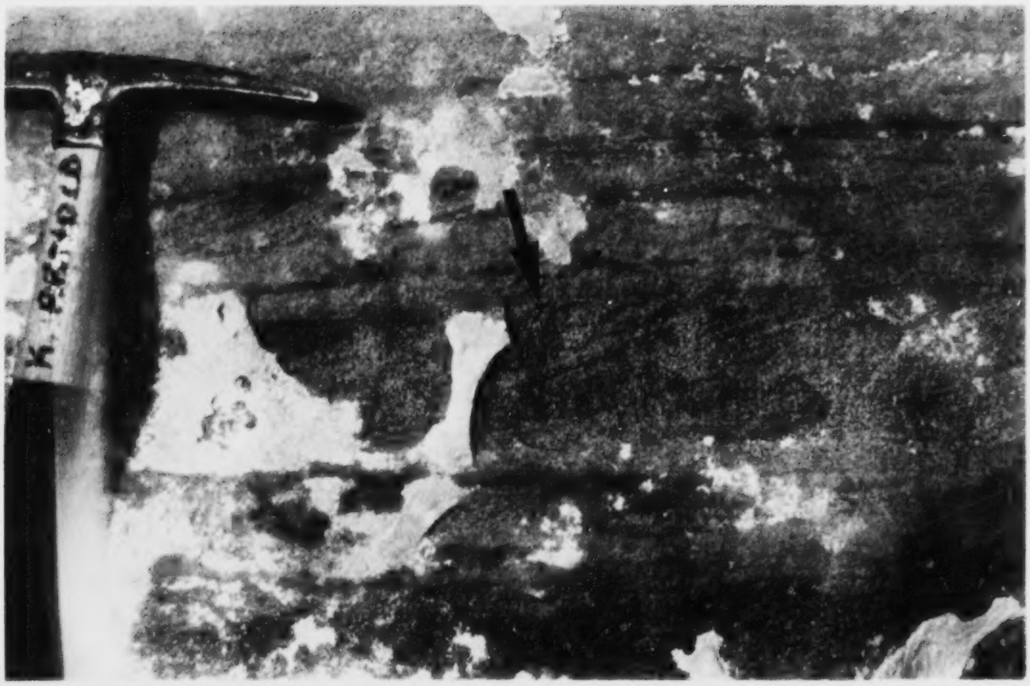


Plate 20. Thin sets of grainflow strata (arrow) between wave rippled sandstones of the ninth aeolian sandstone at the Brown Hill section. Strata represents aeolian migration during periods of sea level rise. Hammer for scale is 25cm long.

while compound/complex barchan dunes have star or smaller barchan dunes superimposed upon them. The dunes of the erg margin are commonly of barchan form.

The dune distribution in modern coastal erg settings of the Namib, Rub' al Khali, sand seas displays a distribution similar to the dune types interpreted in the Charlie Lake Formation. The seaward margin of the dune fields are characterized by simple crescentic (barchan) dunes while the inland portion typically consists of simple, compound or complex linear dunes (Figure 43). The largest and thus the most widely spaced dunes are found in the central parts of the sand sea with progressively smaller dunes towards the margin. The distribution of dune types and size is dependent upon the sand supply and the number and directions of various winds.

At Great Sand Dunes National Monument in Colorado, the dune field was separated into three provinces based upon dune type and sand supply (Figure 31). The first province consists of blowouts and alkaline lakes and is the upwind portion of the aeolian depositional chain. Province 2 consists of extensive sand sheet deposits with parabolic, barchan, and reversing dune forms. The last province is the central erg deposit and consists of transverse and star dune morphologies. The third province is affected by opposing winds resulting in decreased sand movement. In the active state, sand is transported from province 1 which is the source area to province 2 which is the zone of transport to province 3 which is a zone of deposition.

At White Sands National Monument in New Mexico, an evolution of dune forms exists from the upwind source area to the downwind migration path. The forms change (Figure 44) from dome-shaped dunes at the source area, to transverse, to barchan and finally to parabolic dune forms (McKee, 1966).

The Algodones dune field of southeastern California consists of a central portion of compound crescentic draas. The draas are fringed by small and simple crescentic dunes and sand sheets. The dune field is unique because it is migrating oblique to the resultant sand flow direction (Sweet et al., 1988).

It appears that barchan dunes act as sand scavengers and exist where sand supply is scarce. This would explain why barchans are commonly found in the downwind, upwind and lateral margins of sand seas due to the lack of sand supply in these areas (Figure 45). They also act as a carrier for sand, transporting it from source areas to the central erg portion or as the initial transport stages of erg migration. The compound and complex dunes (crescentic, linear, star) form where there is a great quantity of sand being supplied in the

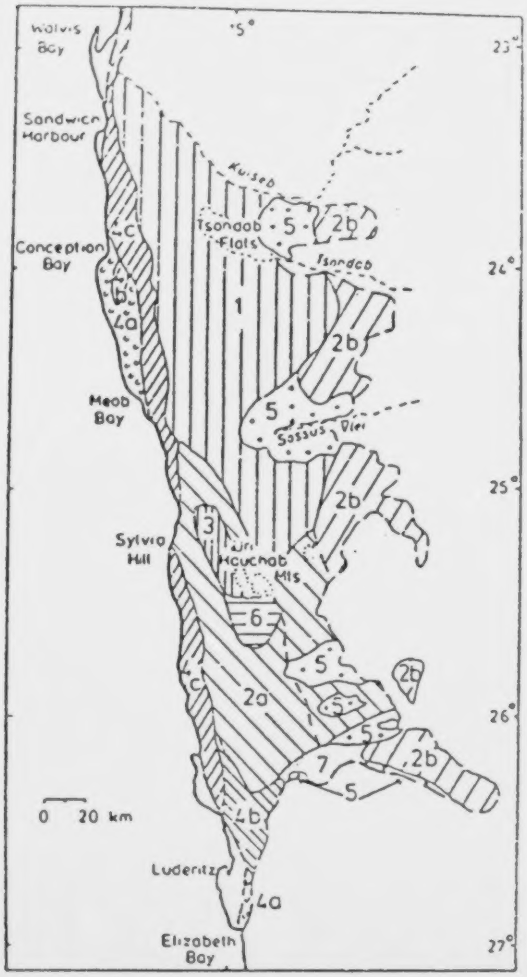

Wolvis Bay
15°
23°
Sandwich Harbour
Kuiseb
Tsondab Flats
5
2b
Tsondab
Conception Bay
c
b
4a
24°
1
2b
Meob Bay
5
Sossus Vlei
25°
2b
3
Sylvia Hill
Uri Hauchab Mts
6
5
2b
c
2a
5
26°
5
7
2b
5
0 20 km
4b
Luderitz
4a
Elizabeth Bay
27°

Figure 43. Dune types in the Namib Sand Sea. Map compiled from LANDSAT imagery and supplemented by air photo interpretation (modified after Lancaster, 1983).

1. Complex linear dunes

2a. Straight crested compound linear dunes

2b. Anastomosing and reticulate patterned compound linear dunes

3. Simple linear dunes

4a. Barchans

4b. Simple transverse and barchanoid ridges

4c. Compound transverse dunes

5. Star dunes and chains of star dunes

6. Rolling dunes without slipfaces

7. Sand sheets

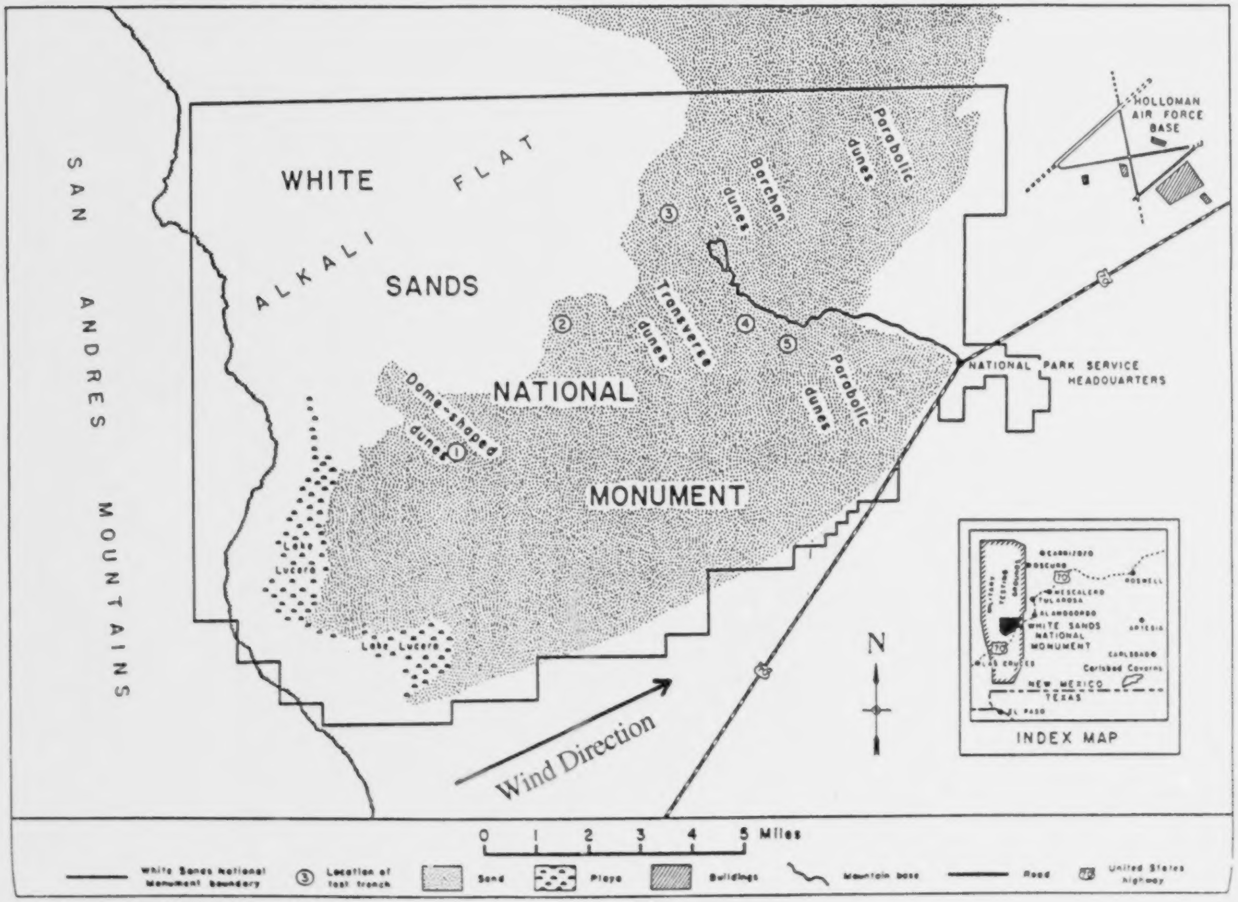

SAN ANDRES MOUNTAINS
WHITE SANDS NATIONAL MONUMENT
ALKALI FLAT
Dome-shaped dunes
Transverse dunes
Barchan dunes
Parabolic dunes
Parabolic dunes
1
2
3
4
5
Lake Lucero
Lake Lucero
HOLLOMAN AIR FORCE BASE
NATIONAL PARK SERVICE HEADQUARTERS
Wind Direction
N
CARRIZOZO
OSCURO
70
ROSWELL
MESCALERO
TULAROSA
ALAMOGORDO
WHITE SANDS NATIONAL MONUMENT
ARTESIA
MILITARY TESTING GROUNDS
70
CARLSBAD
LAS CRUCES
Carlsbad Caverns
NEW MEXICO
TEXAS
EL PASO
INDEX MAP
0 1 2 3 4 5 Miles
White Sands National Monument boundary
Location of test trench
Sand
Playa
Buildings
Mountain base
Road
United States highway

Figure 44. Map of White Sands dune field in New Mexico showing the location of dome, transverse, barchan and parabolic dune forms (modified after McKee, 1966).

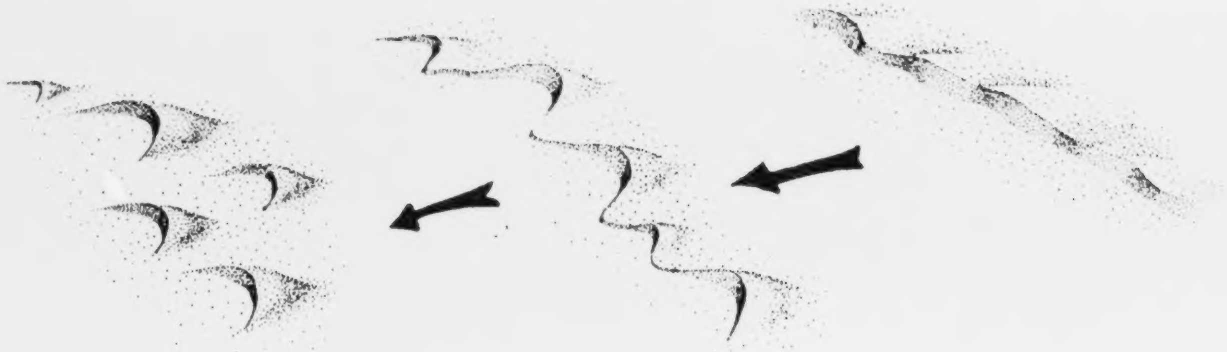


Figure 45. Sequence of dune types with unidirectional wind and diminishing sand supply (right to left); transverse, barchanoid ridge, and barchan (modified after McKee, 1979).

system and therefore act as a sand sink or trap. Sand accumulation usually occurs in the erg centre. In a migrating sand sea, barchans would be the first dune type to migrate over an extradunal surface followed by the central core of simple, compound, or complex dune forms. The migrating nature of the different zones of the sand seas will deposit a vertical succession characteristic of each erg zone.

An idealized facies model for erg migration has been established by Porter (1986, 1987). The model is divided into fore-erg, central-erg and back-erg components (Figure 46). The fore-erg strata records the encroachment of the downwind, leading edge of the sand sea upon flanking depositional environments. Aeolian produced strata typically consists of low angle cross-beds, horizontal stratification and small to medium scale, high-angle cross-beds representing sand sheets, zibars, and small dunes. The fore-erg deposits can exist as pods or lenses encased in marginal marine lithologies or as tongues which extent laterally into thick cross-beds of the central-erg component. The intertonguing occurs as a result of the large-scale oscillations of the fore-erg margin.

The central-erg represents prolonged and uninterrupted aeolian sedimenation and therefore is the thickest of the three erg components. Strata consists of thick, large scale, cross-stratified sandstones. As well, interdune deposits are abundant and highly preserved.

The back-erg deposits form due to the termination of the sand sea by reduction in sand supply, climatic changes, or eustatic sea-level rise. If the deposits are preserved they typically consist of aeolian pods or lenses encased in erg marginal environments. High-angle cross-beds are small-scale and represent small dune forms. Back-erg components in various ancient erg deposits commonly do not exist and are represented by an unconformable surface which caps the erg sequence.

In marine influenced ergs such as the sandstone ergs of the Charlie Lake Formation, fluctuations in sea-level produces abrupt facies transitions on the erg margins. The fore-erg component is expanded in comparison to inland continental erg deposits and represented by a repetition of aeolian sandstones with marine sandstones and carbonates (Porter, 1987). If the duration of the lowstand is sufficient, an abundant sand supply is provided, and bedform organization of the dune field can occur; a central-erg deposit will eventually accumulate (Figure 47).

Rose diagrams indicate Charlie Lake Formation aeolian migration towards the southwest (Figure 16). This transport direction suggests the Charlie Lake ergs are prograding seaward towards the back-barrier lagoon of the Halfway shoreline. Modern coastal ergs

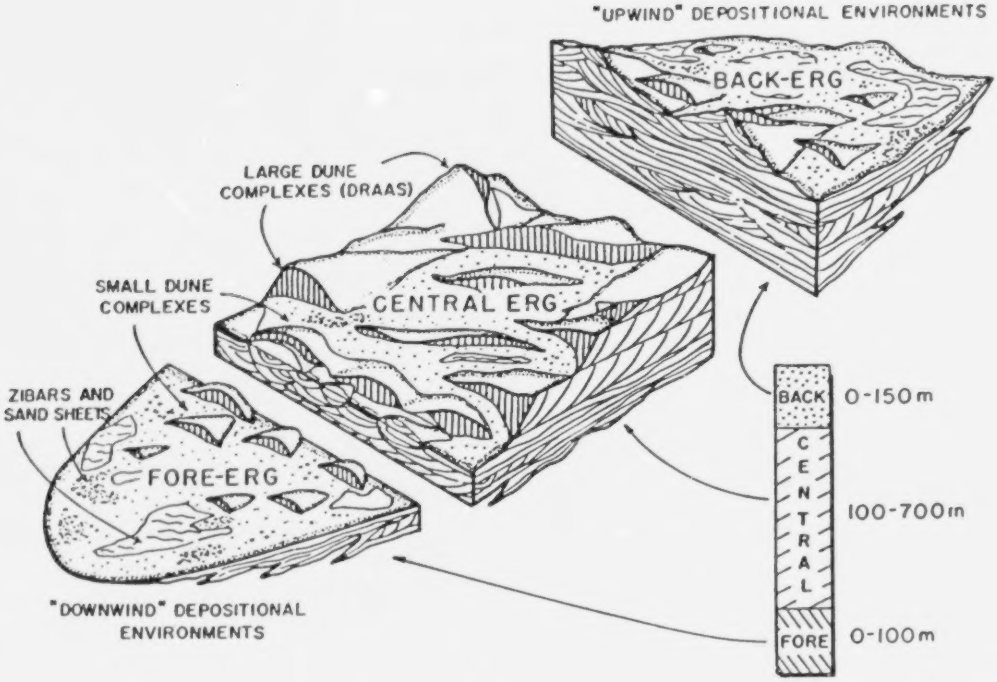

"UPWIND" DEPOSITIONAL ENVIRONMENTS
BACK-ERG
LARGE DUNE COMPLEXES (DRAAS)
SMALL DUNE COMPLEXES
CENTRAL ERG
ZIBARS AND SAND SHEETS
FORE-ERG
"DOWNWIND" DEPOSITIONAL ENVIRONMENTS
BACK
0-150m
CENTRAL
100-700m
FORE
0-100m

Figure 46. Conceptual model of migrating erg. Divisions are based on types and scale of aeolian strata, nature of flanking depositional environment, and sediment dispersal path inferred from cross-bedding. Ideal erg facies sequence is shown for comparative purposes. Many variants of this basic facies arrangement are possible (modified after Porter, 1986).

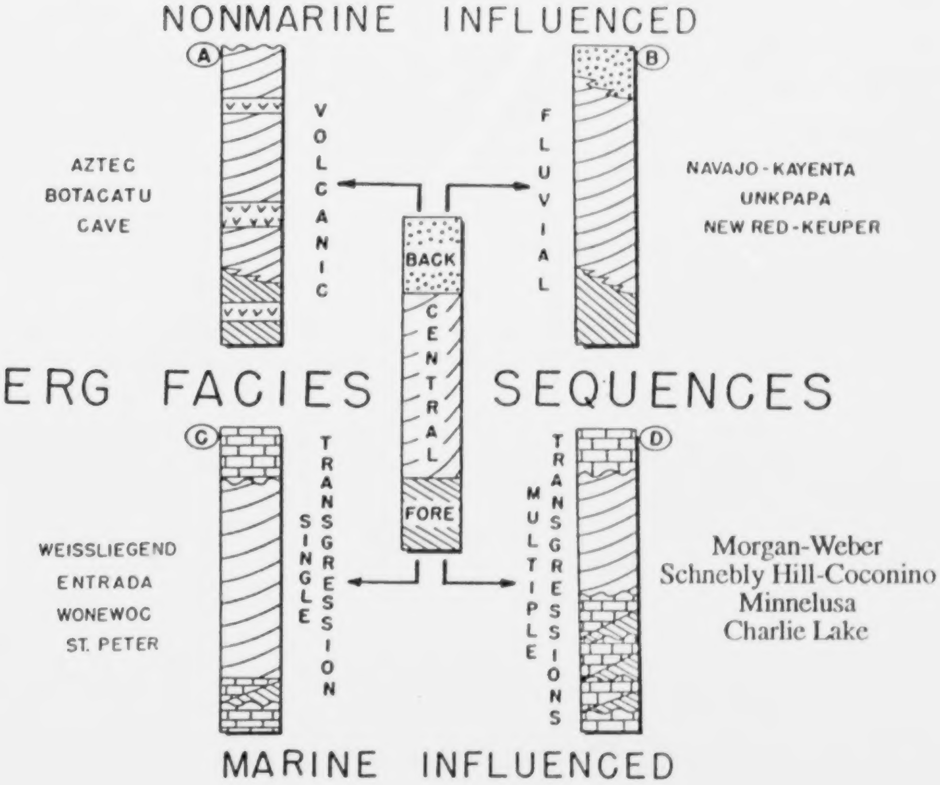

NONMARINE INFLUENCED
A
B
VOLCANIC
FLUVIAL
AZTEC
BOTACATU
CAVE
NAVAJO - KAYENTA
UNKPAPA
NEW RED - KEUPER
BACK
CENTRAL
FORE
ERG FACIES SEQUENCES
C
D
SINGLE TRANSGRESSION
MULTIPLE TRANSGRESSIONS
WEISSLIEGEND
ENTRADA
WONEWOC
ST. PETER
Morgan-Weber
Schnebly Hill-Coconino
Minnelusa
Charlie Lake
MARINE INFLUENCED

Figure 47. Variations in basic erg facies sequences. Nonmarine-influenced cases (A and B) show intertonguing of fore-erg and central-erg strata. Marine-influenced cases show thin or absent fore-erg and back-erg division with single transgression (C) or expanded fore-erg division with multiple transgressions (D). The Charlie Lake sandstones at the Brown Hill section are of type D. Ancient erg examples are shown next to columns (modified after Porter, 1986).

are dominated by simple crescentic (barchan) dune forms nearest the shoreline with larger linear, crescentic and star dune forms inland (Figure 44). The migrating dunes according to Porter's (1986) migrating erg model (Figure 46), would deposit a succession of small-scale cross-beds at the base representing the small crescentic (barchan) dunes overlain by larger cross-beds deposited by the larger inland linear or crescentic dunes. This succession occurs repeatedly in the thicker Charlie Lake sandstones (Figure 19) with small-scale, high-angle cross-beds occurring at the base being interpreted as small barchan dunes and the overlying medium-scale, high-angle cross-beds being interpreted as oblique migrating crescentic or linear dunes.

The small to medium scale high-angle, cross-beds, repetition of aeolian and marine sequences, and the thin nature of the Charlie Lake Formation sandstones are characteristic of fore-erg deposits. Central-erg and back-erg deposits have not been deposited at the Brown Hill section, however the transition from single cross-beds at the base to thicker multiple cross-beds towards the top of the Brown Hill section indicates the progressive encroachment or development of a central-erg deposit with time. The eighth sandstone also contains thicker interdune deposits which are characteristic of central-erg deposits and may reflect the initial migration and development of a central-erg deposit. These downwind fore-erg deposits may be tongues attached to larger central-erg deposits located upwind, or due to a limiting factor such as a small sand supply or insufficient lowstand time, the ergs may not have developed central-erg deposits. Unfortuneately, due to the thin extent of the outcrop, this can not be determined.

In the coastal marine setting, the ergs were ultimately controlled by sea-level fluctuations. Small sea-level rises postponed aeolian development while large sea-level rises terminated aeolian deposition. The small sea-level rises are recorded in the thicker sandstones as interbeds of marine sandstones within aeolian dune sandstones (Figures 34 and 42). The aeolian dunes will migrate to the lagoon water body and with a large sand supply will prograde into the water producing an accretion slope for further erg migration as dune migration will usually outpace any marine regression (Chan and Kocurek, 1988). A small sea-level rise may flood the erg and temperarally terminate aeolian deposition while at the same time reworking the aeolian deposits. When the rise in sea-level ceases, aeolian deposition is reactivated. In a period of multiple small fluctuating sea-level rises, a sequence of interbedded marine and aeolian sandstones will be formed which is documented in sandstones six, eight and nine (Figures 34 and 42). Larger sea-level rises however will permanently terminate aeolian deposition as the magnitude of rise is to great for aeolian processes to compensate. The large sea-level rises or transgressions are recorded as deposits of marine carbonates overlying the aeolian sandstones. Deposition of

Charlie Lake Formation strata was finally terminated by a large transgressive event resulting in the deposition of deep water carbonates of the Baldonnel Formation.

7.0.0 BROWN HILL DEPOSITIONAL MODEL

The depositional model for the Charlie Lake Formation includes a wide range of depositional environments. The components of the model include a clastic barrier island system cut by numerous tidal inlet channels, a back-barrier environment comprising a lagoon and tidal creeks, and an evaporitic coastal plain consisting of peritidal flats, sabkhas, and aeolian dunes (Figure 48).

The Halfway barrier island system has undergone numerous progradational events due to changes in relative sea level (Willis, 1992). The changes in sea level not only affected the positioning of the barrier island but also produces a backbarrier wedge of peritidal deposits that prograde seaward with the clastic shoreline. During prolonged lowstands, and if a sand source was available, aeolian dune fields developed and prograded seaward on the affiliated sabkha plain. Erg development may be associated with the backbarrier facies association of each Halfway parasequence.

The aeolian dunes initially migrated as fore-erg deposits consisting of sand sheets and isolated barchan dunes(Figure 49A). The fore-erg deposits were followed by seaward migrating obliquely orientated transverse or linear dunes which may represent the leading edge of the central-erg deposits (Figure 49B). The ergs prograded seaward until reaching the shoreline or until a prominent sea level rise occurred. This resulted in outpacing of the sand supply to the ergs, thus terminating aeolian deposition (Figure 49C). The extent the erg will prograde seaward depends upon the length of lowstand time. If a sea level rise occurs rapidly after erg development, the erg will be terminated early during its seaward advance. The major flooding event that terminates the erg creates the start of a new peritidal sequence (Figure 49D).

Each sandstone may be a fore-erg tongue of a major central-erg deposit (Figure 50). The central-erg body would be located towards the east in the Charlie Lake subsurface where it has since been removed during pre-Cretaceous erosion (Nordegg unconformity). An alternative model infers the sandstones to be seperate erg bodies (Figure 51) which never fully developed into central-erg deposits due to a diminished sand supply or due to termination of the erg by a rapid change in sea level. The peritidal and aeolian deposits will continue to prograde basinward as long as minor sea level fluctuations occur. The marginal marine successions will cease once a large scale marine transgression occurs leaving the peritidal deposits drowned by a long duration, sea level rise (Figure 51).

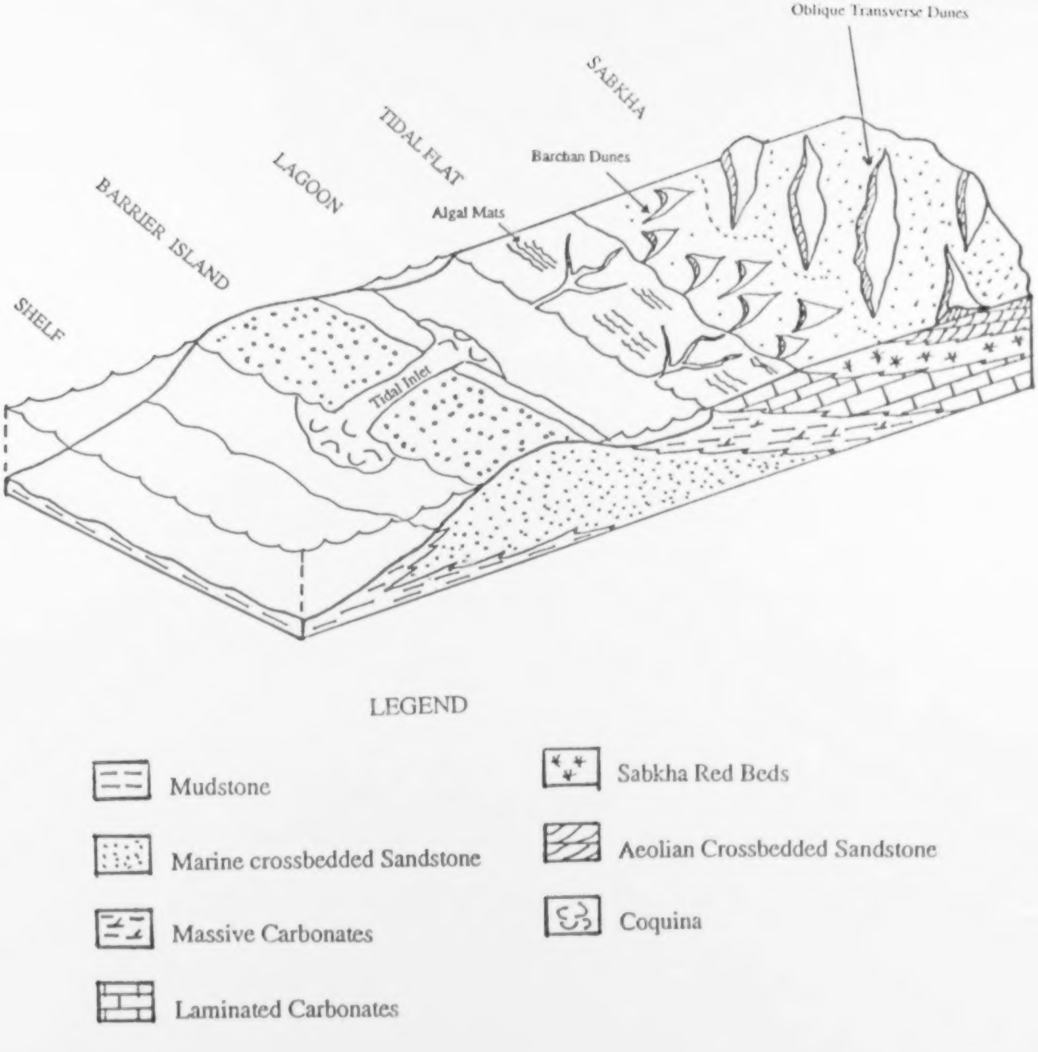

Oblique Transverse Dunes
SABKHA
TIDAL FLAT
Barchan Dunes
LAGOON
Algal Mats
BARRIER ISLAND
SHELF
Tidal Inlet
LEGEND
Mudstone
Marine crossbedded Sandstone
Massive Carbonates
Laminated Carbonates
Sabkha Red Beds
Aeolian Crossbedded Sandstone
Coquina

Figure 48. Three-dimensional depositional model showing inferred depositional environments for the seaward prograding Halfway (shelf, barrier island and tidal inlets) and Charlie Lake (lagoon, tidal flats, sabkha, and aeolian dunes) formations from exposures at Brown Hill. The aeolian dunes are prograding seaward with the initial advance of oblique oriented barchan forms followed by obliquely migrating transverse dunes (modified after Barclay and Leckie, 1986).

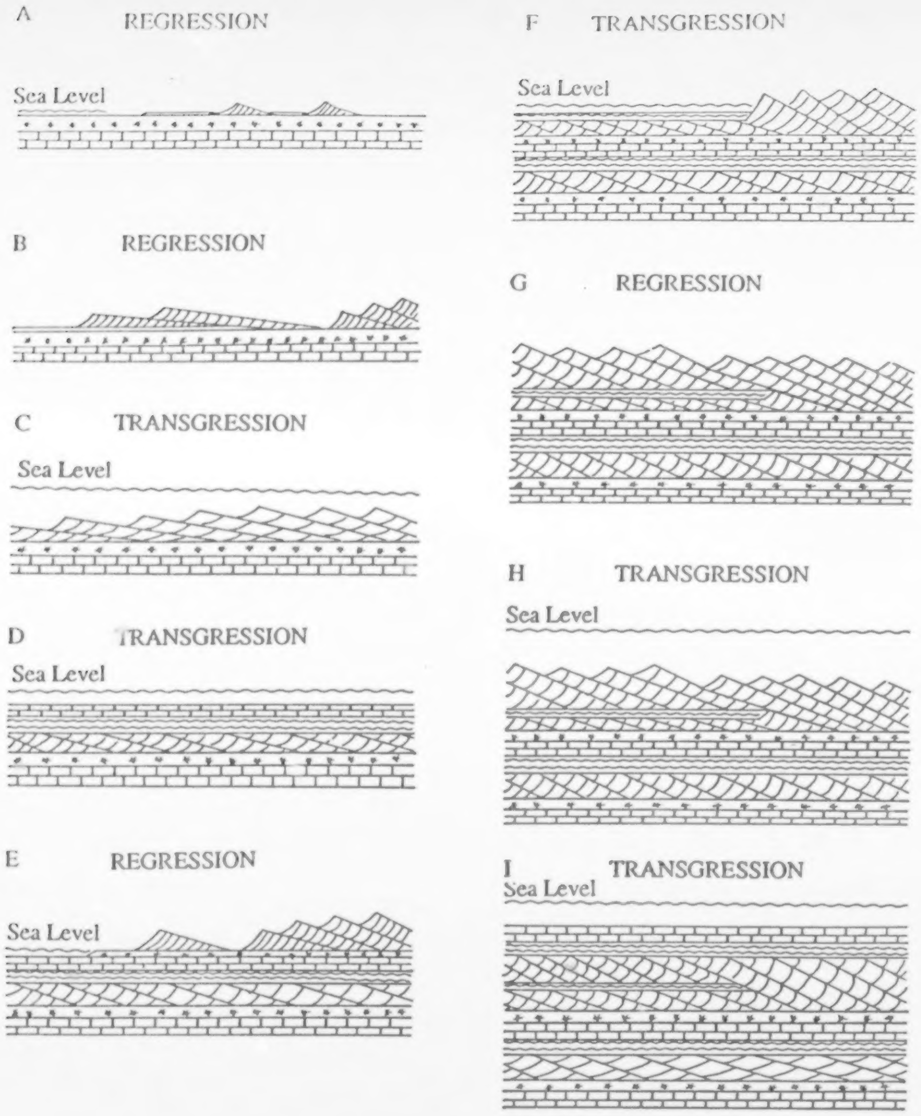

A
REGRESSION
Sea Level
F
TRANSGRESSION
Sea Level
B
REGRESSION
G
REGRESSION
C
TRANSGRESSION
Sea Level
H
TRANSGRESSION
Sea Level
D
TRANSGRESSION
Sea Level
E
REGRESSION
Sea Level
I
TRANSGRESSION
Sea Level

Figure 49. Evolutionary model for the thicker aeolian sandstones of the Charlie Lake Formation at the Brown Hill section. (A) fore-erg deposits prograde seaward on the sabkha plain; (B) central-erg deposits prograde seaward behind the fore-erg deposits; (C) sea level rise floods the erg and terminates aeolian deposition; (D) new peritidal carbonate and evaporite sequence is deposited; (E) renewed erg progradation during next regressive event; (F) a minor sea level rise temporary terminates erg progradation; (G) erg sand supply outpaces sea level rise so erg progradation continues; (H) major sea level rise occurs flooding the erg and terminating aeolian deposition; (I) new peritidal and evaporite sequence is deposited.

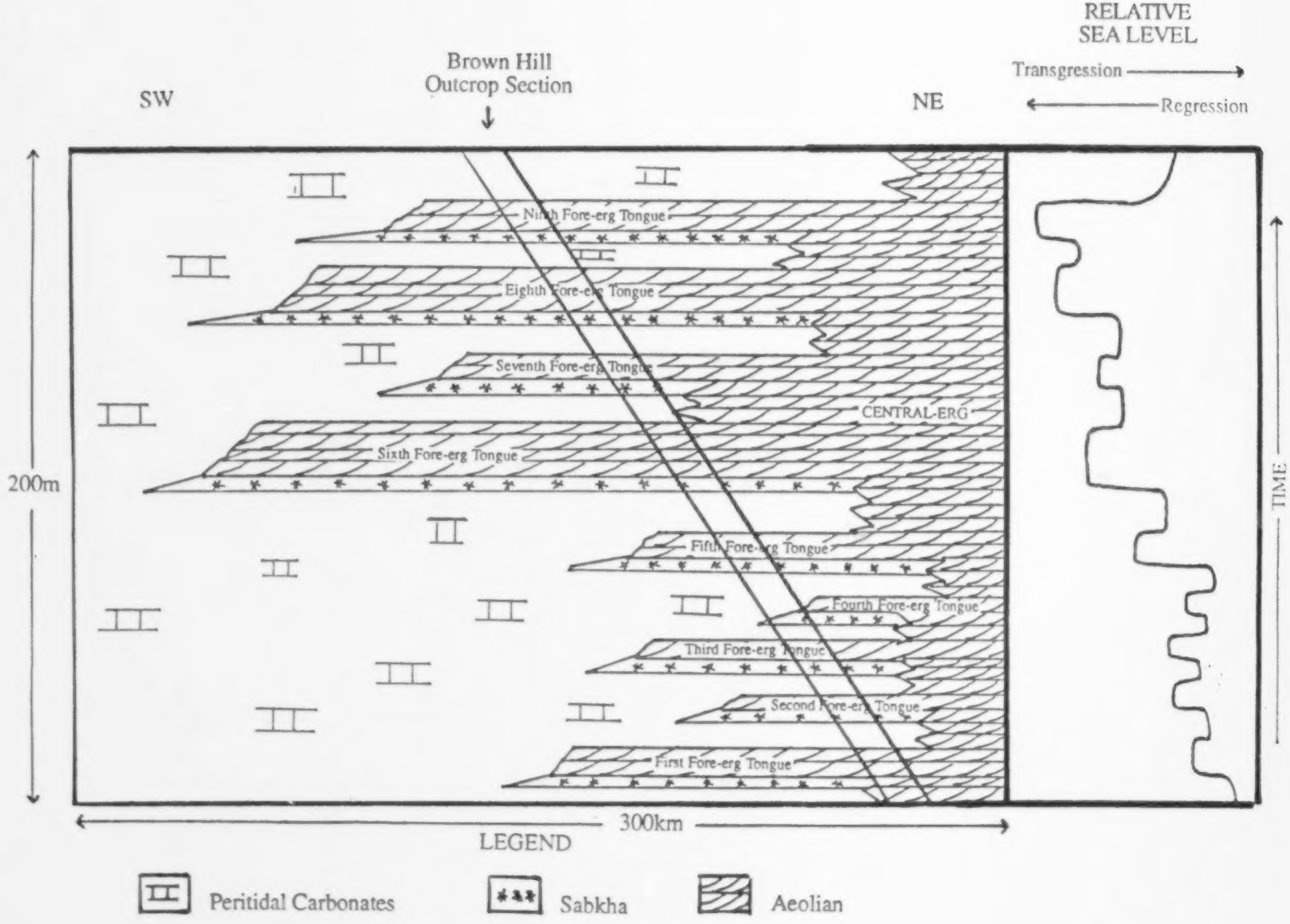

RELATIVE SEA LEVEL
Transgression
Regression
Brown Hill Outcrop Section
SW
NE
Ninth Fore-erg Tongue
Eighth Fore-erg Tongue
Seventh Fore-erg Tongue
CENTRAL-ERG
Sixth Fore-erg Tongue
Fifth Fore-erg Tongue
Fourth Fore-erg Tongue
Third Fore-erg Tongue
Second Fore-erg Tongue
First Fore-erg Tongue
200m
300km
TIME
LEGEND
Peritidal Carbonates
Sabkha
Aeolian

Figure 50. A generalized cross-section illustrating the seaward prograding central-erg model for the aeolian sandstones at the Brown Hill section. Relative sea level trend associated with the fore-erg advances is shown at right.

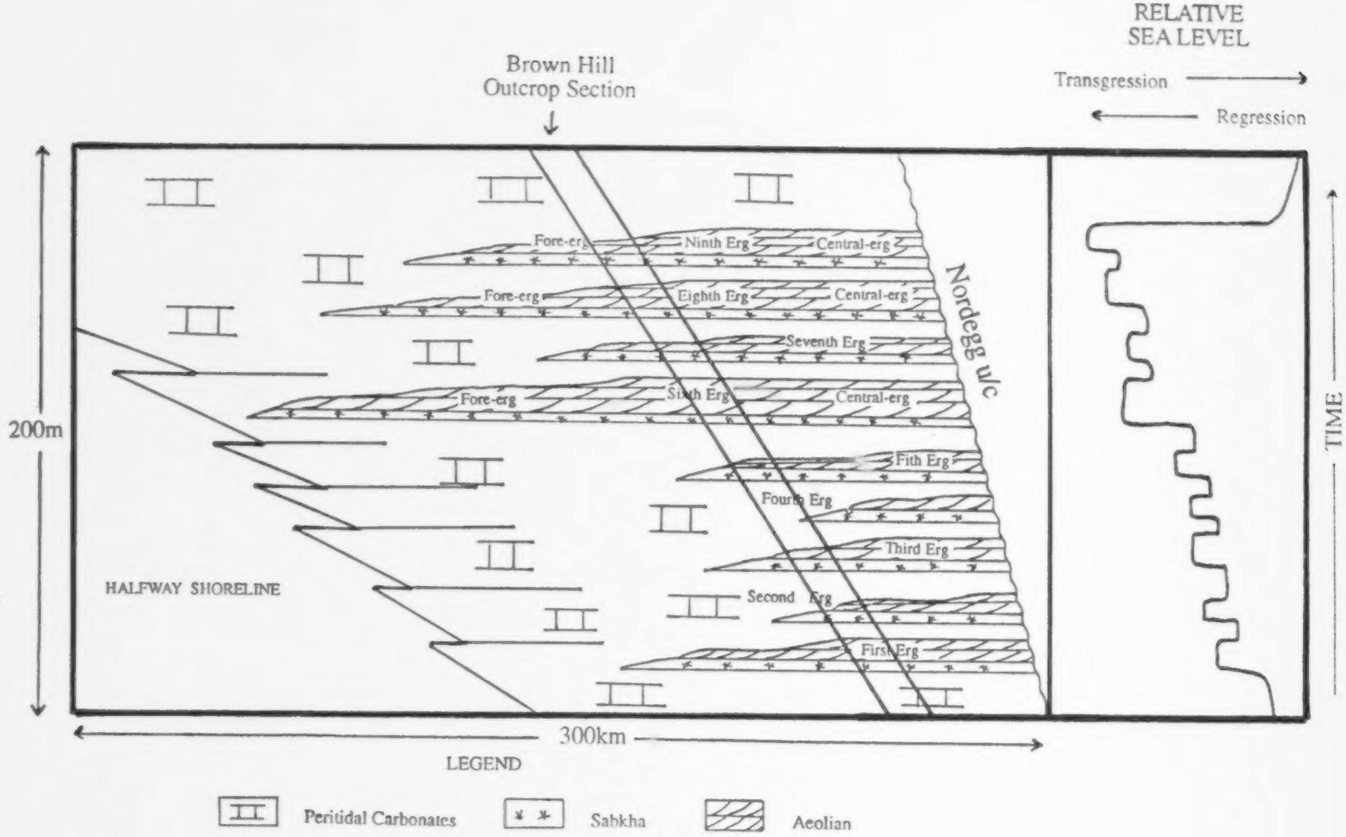

RELATIVE SEA LEVEL
Transgression
Regression
TIME
Brown Hill Outcrop Section
Nordegg u/c
Fore-erg
Ninth Erg
Central-erg
Fore-erg
Eighth Erg
Central-erg
Seventh Erg
Fore-erg
Sixth Erg
Central-erg
Fith Erg
Fourth Erg
Third Erg
Second Erg
First Erg
HALFWAY SHORELINE
200m
300km
LEGEND
Peritidal Carbonates
Sabkha
Aeolian

Figure 51. A generalized cross-section illustrating the seaward prograding coastal erg model for the sandstones at the Brown Hill section as influenced by eustasty. The ergs are re-established when the Halfway sands are subaerially exposed in the east during lowstand events. In this model, each aeolian sandstone is a seperate erg not related to the others.

8.0.0 INGA RESERVOIR SEDIMENTARY FACIES

The lithofacies of the Inga Sandstone including overlying and underlying strata are described and interpreted. Some of the lithofacies appear identical to the lithofacies described from the Brown Hill section. However, these facies are described again to minimize any confusion which may arise from discussions about the lithofacies from either core or outcrop. The various lithofacies of the Inga Sandstone are discussed below and summarized in Table 4.

8.1.0 Facies O. Deformed Siltstones

DESCRIPTION: Facies O consists of a variation of grey, green and red colored siltstones in beds 30cm to 3m thick. The silstone is dominantly red. Occasionally intervals display a gradational change in color from red to green to grey. Upper and lower facies contacts are sharp being either planar or undulatory. The siltstones are dominantly anhydrite cemented and occasionally grade into sandy siltstone intervals. The anhydrite in places accumulates as nodules giving the siltstone a nodular-mosaic or poikiolitic texture. The siltstones are commonly mottled with a vague horizontal plane to the mottling (Plate 21), and occasionally display deformed wavy and planar laminations. In places the siltstone is brecciated. The brecciated clasts are composed of the same siltstone lithology as the underlying siltstone. Some of the thicker siltstone units have 30 to 60 cm long fissures or cracks that are infilled with pink anhydrite. No trace fossils were identified.

INTERPRETATION: The red color of the siltstone is indicative of oxidation during subaerial exposure (Walker, 1979). Other features which suggest subaerial exposure are the brecciated siltstone horizons and the large anhydrite filled fissures. The siltstone can become disaggregated by wind abrasion and by growth and expansion of salt crystals (Kendall, 1969) leaving the siltstone brecciated. The large fissures are produced when the sediment is dewatered under extreme heat causing the sediment to contract and thus split (Loope and Haverland, 1988). The oxidation and subaerial exposure structures are common in supratidal deposits. In arid settings, nodular anhydrite is common in supratidal sediments (Shinn, 1983). The nodules in the siltstones are formed in the capillary zone of the supratidal-flat (Sherman, 1966). The mosaic-nodules of facies O are of this type and add further to the supratidal or sabkha interpretation.

The nodular-mosaic anhydrites are not abundant, as the siltstones are dominated by horizontal mottled sandy siltstone. The mottling is not due to bioturbation as the environment would be too harsh for organisms to survive. The mottling is a result of evaporite formation and growth, and aeolian processes which occur on the sabkha surface. Aeolian processes deflate sediment down to the level of the water table (Andrews and

Facies	Lithology	Bed Thickness	Bedding Features	Physical Sedimentary Features	Biogenic Features	Depositional Environment
O	Deformed Siltstones	30cm-3m	Sharp Planar and Undulatory Contacts	Nodular -mosaic Anhydrite. Haloturbation. Brecciation.	None	Sabkha
P	Laminated Carbonate Mudstone	10cm-5m	Sharp contacts	Wavy laminations. Stylolites. Breccia layers. Fenestral fabric.	Algal Laminations	Intertidal
Q	Peloidal Carbonate Wackestone	10-30cm	Undulatory and sharp contacts. Fining upward.	Wispy laminations.	Pelecypod Fragments. Peloids.	Subtidal (Lagoon)
R	Interlaminated Mud stone and Anhydrite	2cm-3m	Sharp and undulatory contacts	Horizontal laminations. Contorted laminations.	None	Restricted Subaqueous
S	Low-angle Laminated Sandstone	5cm-1.2m	Sharp or gradational upper contacts	Inverse graded laminations inclined at 0-10 degrees. Lag and carbonate chips.	None	Sand Sheet. Dune Apron. Interdune.
T	High-angle Cross-bedded Sandstone	10-60cm	Sharp upper contacts and sharp and undulatory lower contacts	Strata dipping at 20-28 degrees. Avalanche toes.	None	Aeolian Dune
U	Wavy Laminated Sandstone	2-60cm	Sharp Contacts	Asymmetrical ripples. Salt ridge structures.	None	Interdune. Marine.
V	Deformed Sandstone	3cm-2m	Lower contact is sharp or gradational. Upper contact is sharp.	Contorted sandstone. Sandstone clasts in contorted sandstone.	None	Marine Reworked Aeolian. Accretion Slope.
W	Massive Sandstone	3-40cm	Sharp contacts	Massive	None	Aeolian Dune. Marine Reworked Aeolian.
X	Sandy Carbonate Mudstone	50-70cm	Sharp and undulatory contacts	Sand % decreases upward.	None	Subtidal (Lagoon)

Table 4. Summary of lithofacies identified within, above and below the Inga Sandstone in the subsurface of northeastern British Columbia.

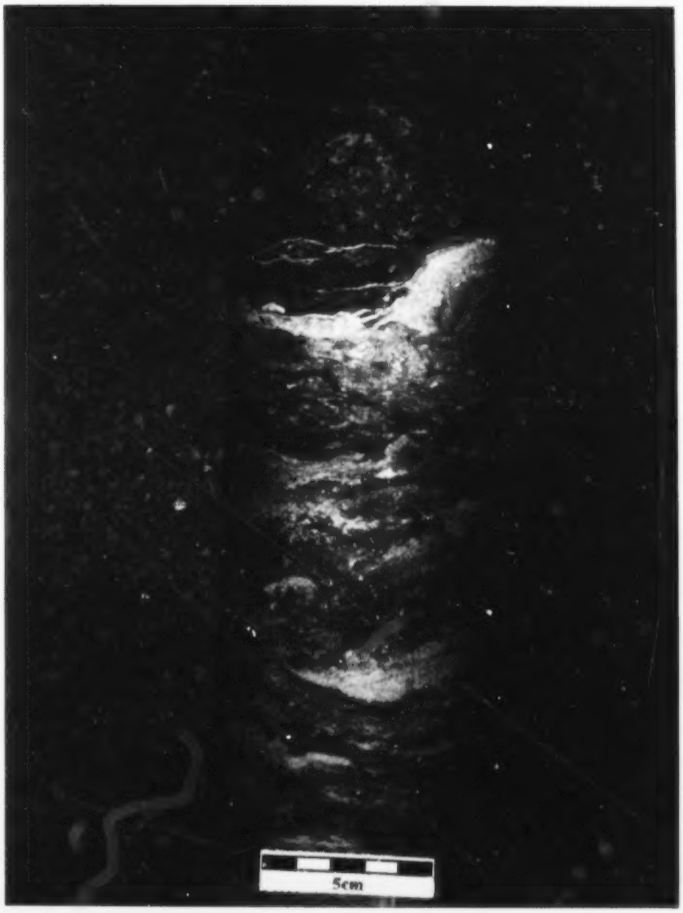


Plate 21. Horizontal wavy, indistinct bedding caused by haloturbation in siltstone of facies O. The white markings in the facies are anhydrite cement. Well 16-4-87-23W6; 1535.3m.

Higgins, 1984). The exposed surface at the water table is damp. Silt and sand blown across the surface will adhere and accumulate on the surface. During drying cycles, salt will concentrate at the air-sand interface because of evaporation of saline capillary water along the water table surface (Fryberger et al., 1983) forming a crust. As the salts expand, the layers of silt, sand and anhydrite become buckled and deformed. Continued deposition would produce a deformed or mottled succesion with a seemingly horizontal wavy, indistinct bedding. The grain size within the siltstones is due to the size of the grains entrained in the wind. The gradual change from silt to sand may coincide with the encroachment of an erg margin. As the erg approachs there will be more sand in the wind currents therefore more sand will adhere to the water table surface.

Facies O is interpreted as sabkha (supratidal) deposits that accumulated on broad featureless flood and coastal plains. However there are two types of sabkhas represented in the siltstones. The mosaic-nodular siltstones are representative of a more proximal position to the coastline whereas the mottled siltstones represent a more inland position on these flood plains (Handford, 1981). This facies is absent at the Brown Hill section but may have been removed during solution brecciation of facies J.

8.2.0 Facies P. Laminated Carbonate Mudstone

DESCRIPTION: This facies is light brown to beige in color, commonly oil stained and occurs in beds 10cm to 5m thick. The facies is dominantly a dolomitic mudstone with occasional peloid packstone interbeds, and 1.0 to 2.0 mm thick crenulated laminations. The crenulation partings are black and discontinuous. Stylolites are common. Small 1mm sized voids occur in horizontal displacement throughout the laminations. Occasionally a breciated bed or layer occurs among the laminated dolostone beds (Plate 22). The breccia layers are 3 to 10cm thick and the clasts are composed of the same laminated dolostone beds which occur above and below. The clasts are angular and orientated horizontally as if the brecciated layers have just been pulled apart. The facies displays a randomly dispersed anhydritic poikiolitic texture. The upper and lower contacts are sharp and undulatory. Laminated dolostones commonly overly deformed siltstones (facies O) and peloidal carbonates (facies Q) with sharp contacts. Facies P is overlain and grades into interlaminated mud and anhydrite (facies R).

INTERPRETATION: The laminated carbonate facies has characteristics common to intertidal zones of the Persian Gulf (Kinsman, 1964; Illing et al., 1965; Kendall and Skipwith, 1969; Shinn, 1983). The crenulated, discontineous laminations within micritic carbonate mud may have formed by algal mat growth between daily flooding episodes in which mud settles from suspension over the once exposed algal mats. Stronger flood

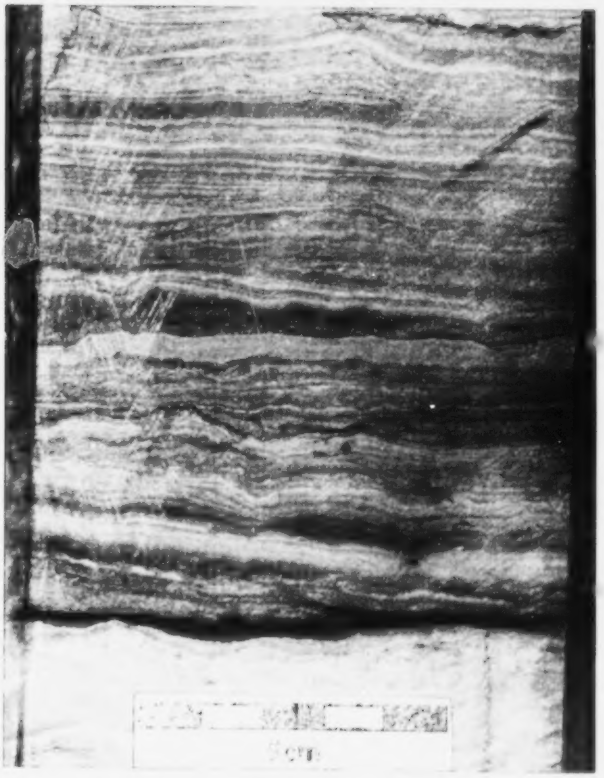


Plate 22. Laminated carbonates of facies P. The laminations consist of interlaminated carbonate mud and algal mat. Well 6-4-85-23W6; 1448m.

oriented currents may transport peloids from the subtidal zone onto the intertidal flats. Other sedimentary features that indicate subaerial exposure are the brecciated layers which occur between the laminated carbonates. During extended conditions of exposure, the laminations dried and cracked (dessication) and then were flooded again depositing alternating beds of brecciated and laminated carbonates. The voids in the facies may yield a fenestral fabric formed by shrinkage and expansion of sediments, gas bubble formation, escaping air during flooding, or as wrinkles in algal mats (Shinn, 1983), or by the dissolution of evaporites. The sedimentary structures suggest an upper intertidal environment in which the facies is subjected to cyclic flooding and exposure. Facies P is the equivalent of facies I at the Brown Hill section.

8.3.0 Facies Q. Peloidal Carbonate Wackestone

DESCRIPTION: The peloidal carbonates are a light brown to cream white color and grade from packestones to wackestones to micritic mudstones. The facies occurs in thin beds 10cm to 30cm thick. The individual peloids are subspherical, about 0.5mm thick and lack internal structure. The peloids often form as aggregates or clusters. There are no sedimentary structures observed except 1mm thick black mud wispy laminations (Plate 23). The peloids are in a micritic dolostone/mudstone matrix. Occasionally the facies contains pelecypod fragments which have been recrystallized by dolomite. The pelecypod fragments constitute 5% of the facies when present. The upper and lower contacts of the beds are sharp and undulatory. The facies generally overlies facies O and is overlain by facies P and R.

INTERPRETATION: In the modern Trucial Coast, pellets and gastropods are both common in the subtidal lagoon (Purser and Evans, 1973). Peloids have been suggested to orginate as fecal pellets deposited by grazing and burrowing organisms in quiescent subtidal settings. The presence of pelecypod fragments indicates a less stressful marine environment such as a subtidal lagoon. The small diversity however suggests the lagoon may be slightly restricted. Wispy laminations are believed to originate from burrowing and microstylolitization which obliterate primary sedimentary structures and preserving only the wispy laminations (Fracasso and Hovorka, 1986). Facies Q is equivalent to Facies H of the Brown Hill section.

8.4.0 Facies R. Interlaminated Mud and Anhydrite

DESCRIPTION: The interlaminated mud and anhydrite consists of fine laminations of mud and anhydrite in beds 2cm to 3m thick. The anhydrites appear as a grey, purple or blue color while the muds are brown or black. The muds are dolomitized. The laminations dominantly occur as uneven and wavy or undulatory bands. Occasionally the laminations

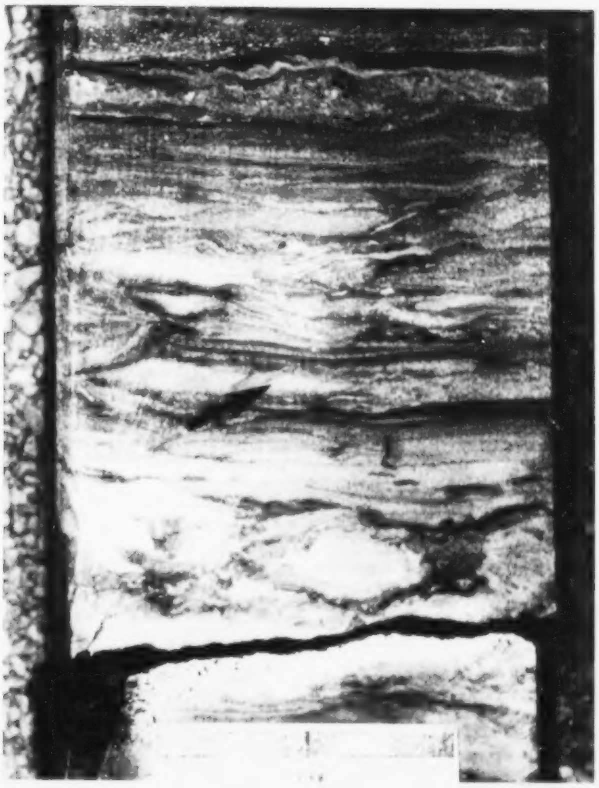


Plate 23. Wispy laminations in peloidal carbonates of facies Q. The white patches (arrow) are aggregates of peloids. Well 6-32-85-23W6; 1632.9m. Scale bar is 5cm long.

are crinkly or highly contorted (Plate 24). The upper and lower contacts are always sharp being planar or undulatory. No other sedimentary or biogenic structures were identified.

INTERPRETATION: The bedded nature of the anhydrite is typical of deposition within a subaqueous water body (Schreiber, 1988). The precipitation of anhydrite indicates the water was very saline and that the water body was likely restricted creating an enclosed basin (Roy, 1972). The laminated nature is produced by the formation of evaporite crystals at the air/water interface which settle out onto the basin floor from suspension (Dean and Anderson, 1978). Eventually the basin dries or completely evaporates and is followed by deposition of sabkha muds and silts (facies O). The irregular contact between the two facies is produced by subaerial exposure. Facies R is absent at the Brown Hill section but is likely represented by the solution breccias of facies J.

8.5.0 Facies S. Low-angle Laminated Sandstone

DESCRIPTION: Facies S consists of grey to white colored low-angle finely laminated sandstone. The color is from the abundant anhydrite cement. Facies S occurs in beds 5cm to 1.2m thick. The laminations are 1mm thick and dip at angles less than 10 degrees (Plate 25). The sand is made of lower and upper fine grained particles which are inversely graded. The occasional granule grain or 1 to 2 mm long carbonate chips (Plate 26) are dispersed among the laminations. The laminations have a pin stripe texture due to cement differentiation. The sand is moderately sorted and is occasionally oil stained. The low-angle laminations sometimes grade upward into the high-angle cross-beds of facies T but usually are capped by a horizontal planar contact. Trace fossils were not identified.

INTERPRETATION: The inverse grading of the laminations, sand size, and the positioning between high-angle cross-beds of facies T are characteristics of aeolian deposition (Hunter, 1977). There are three different aeolian environments where low-angle laminations are abundant and these are interpreted to occur in the Inga Sandstone. Low-angle aeolian laminations can be deposited by migrating wind ripples in dry interdune areas, as sand sheet deposits, or as dune apron deposits at the base of a slipface and on parts of dunes where a slipface is not developed such as the plinths of linear and star dunes or the horns of barchanoid dunes (Kocurek, 1986).

Interdune deposits are formed when dunes and their associated interdunes migrate and climb leaving a vertical alteration of flat lying strata and dune cross-strata. Interdunes are best associated with the generation of first-order bounding surfaces produced by the migration of dunes and draas (Kocurek, 1988). The thickness of the interdune deposits are dependent upon the dune type and its rate of migration. Fast moving barchan dunes will

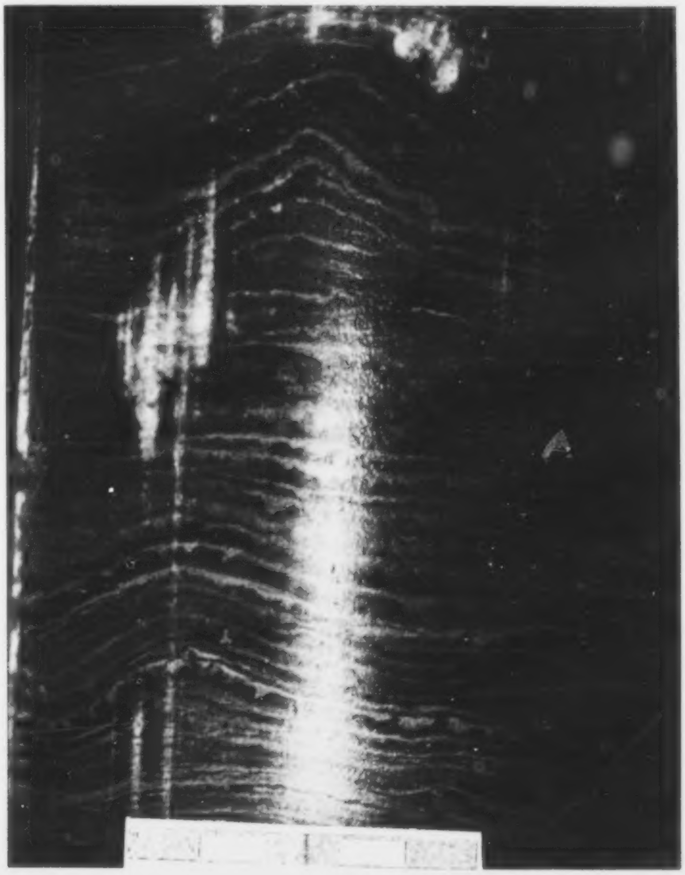


Plate 24. Contorted strata in interlaminated mud and anhydrite of facies R. Well C-16-J 94-A-12; 1613.7m. Bar scale is 5cm long.

Plate 25. Low-angle, horizontal laminated sandstone (arrow) of facies S. The laminations are inclined at an angle of 8 degrees. Strata is interpreted as interdune deposits because of its positioning between high-angle cross-bedded sandstone of facies T. Well 6-28-87-23W6; 1619m. Bar scale is 5cm long.

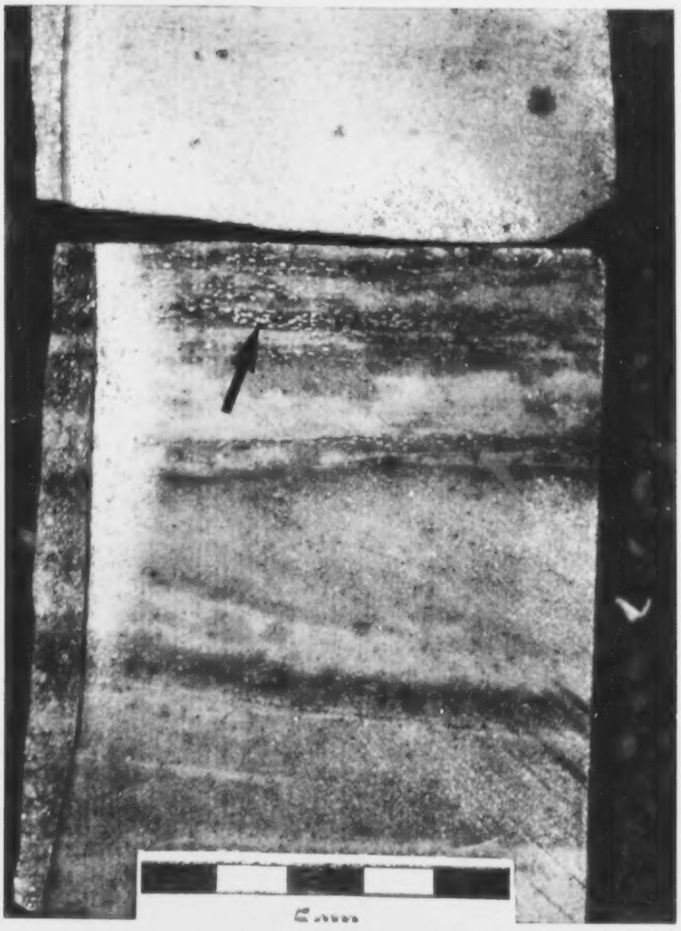


Plate 26. Carbonate chips (arrow) dispersed among low-angle laminated sandstone of facies S. The chips are lag deposits on interdune floors. Well 6-33-87-23W6; 1644.8m. Bar scale is 5cm long.

leave a thin interdune deposits (1mm to 1cm) or just a lag deposit while more stationary star types deposit a thick interdune succession (m) (Lancaster and Teller, 1988). The low-angle laminations deposited between high-angle cross-beds of facies T are interpreted as interdune deposits produced by the migration of wind ripples migrating across the interdune surface (Figure 52). The bounding surfaces and low-angle laminations with coarse to granule size deposits are interpreted as grains too large to be removed by wind processes and left as a lag deposit on the interdune floor. The elongate carbonate chips originated as an exposed carbonate surface which was subject to dessication and was incorperated as a lag in the interdune deposit.

Sand sheets occur in areas of aeolian sands when dune deposits are usually absent (Fryberger et al., 1979). Sand sheets commonly occupy the margins of ergs. This positioning on the erg margin suggests that their deposits should occupy the basal, upper and lateral portions of the erg. Low-angle laminations at the base of an aeolian sequence may represent the migration of the erg or the initial phase of erg development (Kocurek, 1986). Sand sheet deposits have sheet-like geometries that span several km which help to discriminate them against the less lateral interdune deposits. The thick, low-angle laminations at the base of the Inga aeolian sequences are interpreted as sand sheet deposits and may represent the initial organization of the Inga erg (Figure 53). Inga aeolian sequences entirely composed of low-angle laminations represent sand sheet deposits on the margins of ergs.

Low-angle strata deposited at the base of slipfaces as aprons rarely occur in the Inga Sandstone (Figure 54). Strata of this type generally grade upward into higher angle grainflow or grainfall strata as bottomsets and are not separated by a planar bounding surface (Heward, 1991). These alternating strata of grainflow (facies T) and wind ripple strata are produced by primary winds associated with the slipface advance which are punctuated by periods with lee-eddy winds which blow along or up the lee face (Hunter, 1981). Small apron deposits are common to transverse dune types because the grainfall deposits generally do not reach the base and the back-eddy roller is too weak to transport sand from the interdune area back onto the slipface (Hunter, 1981).

8.6.0 Facies T. High-angle Cross-bedded Sandstone

DESCRIPTION: Facies T consists of grey to white colored high-angle cross-bedded sandstone. The grey and white color is due to the dominance of anhyrite cement. The facies is commonly oil stained and therefore appears brown. Facies T occurs as 10cm to 60cm thick beds. The high-angle strata occurs in laminations 1-2cm thick and are distinctand even-textured dipping at angles of 20 to 28 degrees (Plate 27). Occasionally the

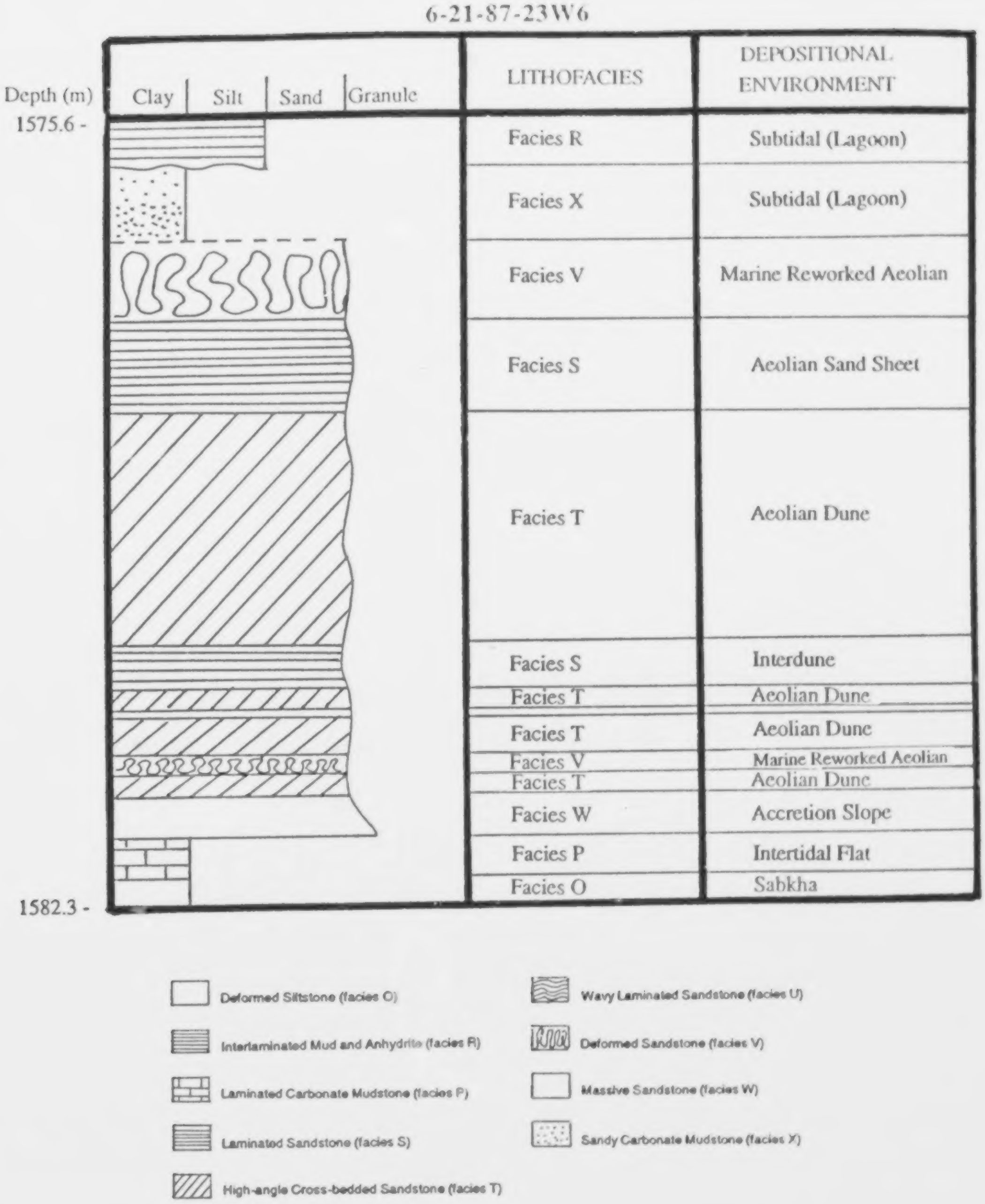

6-21-87-23W6
Depth (m)
Clay
Silt
Sand
Granule
LITHOFACIES
DEPOSITIONAL ENVIRONMENT
1575.6 -
1582.3 -
Facies R
Subtidal (Lagoon)
Facies X
Subtidal (Lagoon)
Facies V
Marine Reworked Aeolian
Facies S
Aeolian Sand Sheet
Facies T
Aeolian Dune
Facies S
Interdune
Facies T
Aeolian Dune
Facies T
Aeolian Dune
Facies V
Marine Reworked Aeolian
Facies T
Aeolian Dune
Facies W
Accretion Slope
Facies P
Intertidal Flat
Facies O
Sabkha
Deformed Siltstone (facies O)
Interlaminated Mud and Anhydrite (facies R)
Laminated Carbonate Mudstone (facies P)
Laminated Sandstone (facies S)
High-angle Cross-bedded Sandstone (facies T)
Wavy Laminated Sandstone (facies U)
Deformed Sandstone (facies V)
Massive Sandstone (facies W)
Sandy Carbonate Mudstone (facies X)

Figure 52. Sedimentary sequence of the lithofacies of the Inga Sandstone at well location 6-21-87-23W6 including an interpreted sedimentologic depositional environment.

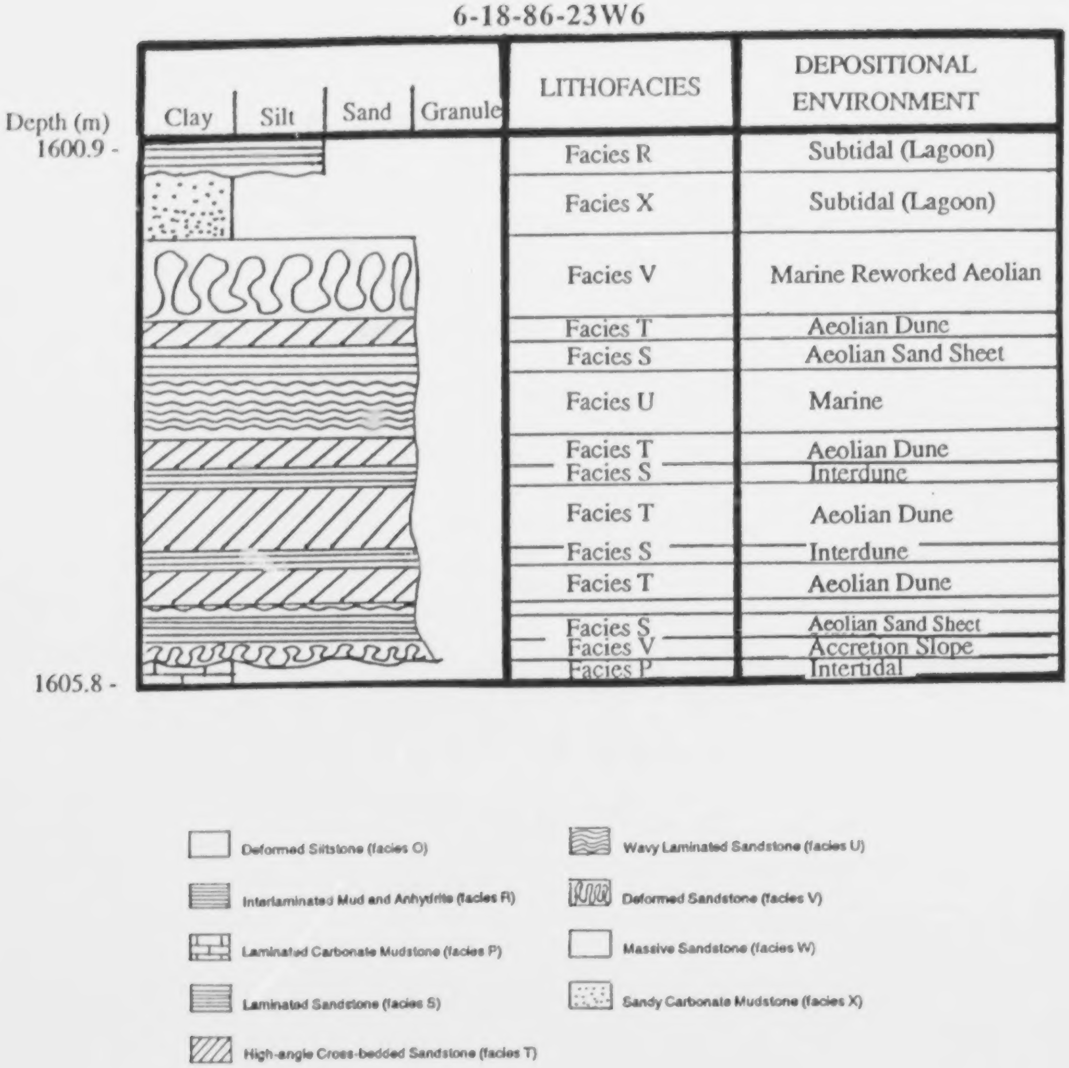

6-18-86-23W6
Depth (m)
1600.9 -
1605.8 -
Clay
Silt
Sand
Granule
LITHOFACIES
DEPOSITIONAL ENVIRONMENT
Facies R
Subtidal (Lagoon)
Facies X
Subtidal (Lagoon)
Facies V
Marine Reworked Aeolian
Facies T
Aeolian Dune
Facies S
Aeolian Sand Sheet
Facies U
Marine
Facies T
Aeolian Dune
Facies S
Interdune
Facies T
Aeolian Dune
Facies S
Interdune
Facies T
Aeolian Dune
Facies S
Aeolian Sand Sheet
Facies V
Accretion Slope
Facies P
Intertidal
Deformed Siltstone (facies O)
Interlaminated Mud and Anhydrite (facies R)
Laminated Carbonate Mudstone (facies P)
Laminated Sandstone (facies S)
High-angle Cross-bedded Sandstone (facies T)
Wavy Laminated Sandstone (facies U)
Deformed Sandstone (facies V)
Massive Sandstone (facies W)
Sandy Carbonate Mudstone (facies X)

Figure 53. Sedimentary sequence of lithofacies of the Inga Sandstone at well location 6-18-86-23W6 including an interpreted sedimentologic depositional environment.

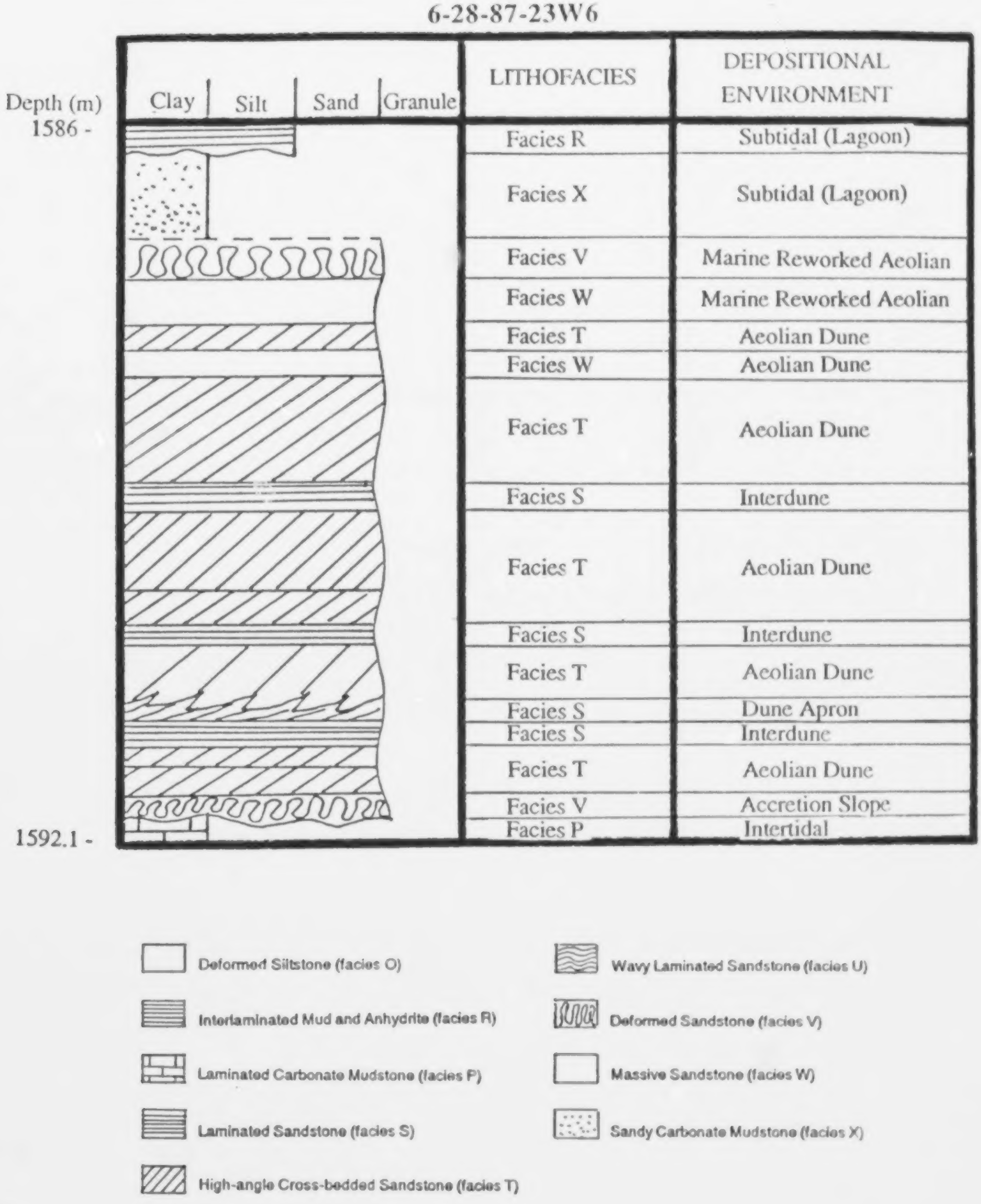

6-28-87-23W6
Depth (m)
1586 -
1592.1 -
Clay
Silt
Sand
Granule
LITHOFACIES
DEPOSITIONAL ENVIRONMENT
Facies R
Subtidal (Lagoon)
Facies X
Subtidal (Lagoon)
Facies V
Marine Reworked Aeolian
Facies W
Marine Reworked Aeolian
Facies T
Aeolian Dune
Facies W
Aeolian Dune
Facies T
Aeolian Dune
Facies S
Interdune
Facies T
Aeolian Dune
Facies S
Interdune
Facies T
Aeolian Dune
Facies S
Dune Apron
Facies S
Interdune
Facies T
Aeolian Dune
Facies V
Accretion Slope
Facies P
Intertidal
Deformed Siltstone (facies O)
Interlaminated Mud and Anhydrite (facies R)
Laminated Carbonate Mudstone (facies P)
Laminated Sandstone (facies S)
High-angle Cross-bedded Sandstone (facies T)
Wavy Laminated Sandstone (facies U)
Deformed Sandstone (facies V)
Massive Sandstone (facies W)
Sandy Carbonate Mudstone (facies X)

Figure 54. Sedimentary sequence of the lithofacies of the Inga Sandstone at well location 6-28-87-23W6 including an interpreted sedimentologic depositional environment.

lamina taper down-dip into a wedge toe. Sand in the laminations are well sorted and dominately upper fine grained. Some cores show horizontal planar upper and lower contacts which occasionally have 1 to 2mm long granules and carbonate chips along the surface. Trace fossils were not identified.

INTERPRETATION: The stratigraphic positioning of facies T between aeolian wind ripple produced low-angle laminations of facies S (Figures 52 and 53) indicates the high-angle cross-bedded sandstones are also of aeolian origin. Strata inclined at high angles are deposited on the slipfaces of aeolian dunes. The distinct and even textured 1-2cm thick strata are characteristic of sandflow strata which is produced by the avalanching of sand down the slipface of aeolian dunes (Hunter, 1977). The presence of avalanche toes at the base of some of the structures verifies the sandflow origin. Each 1 to 2cm thick stratum represents a single avalanche event. The planar contacts separating cross-bed sets are bounding surfaces. Being unable to laterally trace the bounding surfaces, it is unknown if they are first, second or third order surfaces. However, the lack of interdune deposits suggests the surfaces are either second or third order (Kocurek, 1981). The granules and carbonate chips are lag deposits which accumulate on interdune floors and were buried by the migrating dunes. Facies T is equivalent to facies K of the Brown Hill section.

8.7.0 Facies U. Wavy Laminated Sandstone

DESCRIPTION: Facies U consists of grey to white, lower to upper fine grained sandstone. The sand is anhydrite cemented and is moderately sorted. The facies consists of symmetrical ripple laminations which are slightly deformed (Plate 28). The deformation increases in abundance upwards through each bed. The ripple-form beds are 2cm to 60cm thick. The upper and lower contacts are sharp and horizontally planar. The rippled sandstone commonly overlies high-angle cross-bedded sandstones of facies T or deformed sandstone of facies V and is overlain by low-angle laminated sandstones of facies S. No trace fossils were identified.

INTERPRETATION: The rippled sandstone facies which becomes more deformed upwards is interpreted as a "drying-upward" sequence. Facies U commonly overlies deformed sandstone of facies V which is deposited as a result of marine transgression (Figures 55 and 56). As the transgressive water body starts to evaporate and shallow, ripples are replaced by salt ridge structures. Salt ridges form from the concentration of halite at the air-sand interface because of evaporation of saline capillary water (Fryberger et al., 1983). The resulting excess material at the surface causes expansion, forcing portions of the cemented layer to rise producing deformed ripple like structures. The wave ripples may be deformed due to penecontemporaneous evaporation which deposits evaporites with

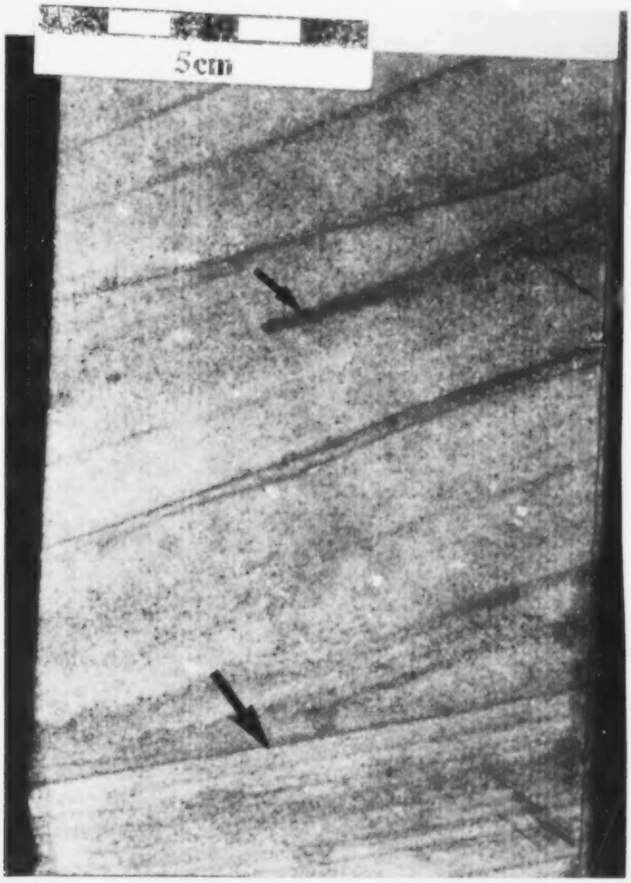


Plate 27. High-angle cross-bed of sandflow strata of facies T. Note that some of the avalanche stata is toeing out (small arrow). The high-angle cross-bed overlies low-angle laminations of facies S seperated by a bounding surface (large arrow). Well 16-9-87-23W6; 1588m.

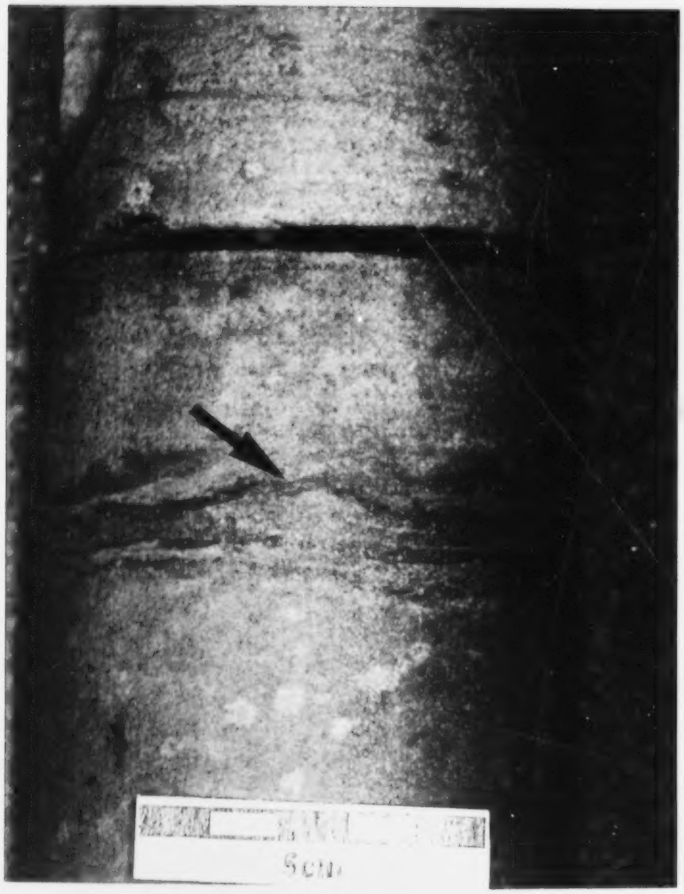


Plate 28. Possible wave ripple (arrow) of facies U which has been deformed by haloturbation (salt growth). Facies U is overlain by low-angle laminated sandstone of facies S. Well 14-21-87-23W6; 1617.8m. Scale bar is 5cm long.

the ripples which later expand and cause the deformation. The thicker sequences of facies U may be similar in origin to facies M of the Brown Hill section which are caused by high tidal flooding while the thin (1 to 3cm) beds may be interdune deposits (figure 55) formed by high water tables (Andrews and Higgins, 1984). As the drying cycle continues, the deformed ripples are overlain by aeolian deposits (Figure 53) usually of wind ripple or sand sheet origin (facies S). Facies U may be the equivalent of facies M of the Brown Hill section.

8.8.0 Facies V. Deformed Sandstone

DESCRIPTION: The deformed sandstone occurs as 3cm to 2m thick beds that occur in several different stratigraphic assemblages. Most common, the deformed sandstone is interbedded with other Inga Sandstone lithofacies, but at the margins of the Inga reservoir, the entire Inga interval consists of deformed sandstone. The Inga Sandstone is always encased above and below by deformed sandstone. The facies is grey to white in color and is anhydrite cemented. The sandstone is dominantly lower to upper fine grained however the deformed sandstone at the base commonly has lower medium grained sand and less occasionally 1 to 2 cm long limestone clasts (Plate 29). The deformation (Plate 30) in the upper capping deformed bedoccasionally occurs as 1cm to 4cm thick deformed clasts within a matrix of deformed sand (Plate 31). The lower encasing deformed bed has a lower contact that is gradational or is undulatory erosional while the upper deformed bed has an upper contact that is commonly sharp and less frequently gradational. Trace fossils were not identified in this lithofacies.

INTERPRETATION: The deformed strata at the base of the Inga Sandstone (Figures 53, 54, 55 and 56) is the initial migration of the aeolian sand over the sabkha into the very shallow intertidal waters forming the accretion slope of Shinn (1973). The accretion slope consists of marine reworked aeolian sand. The sand may have originally been inclined seaward as in Fryberger et al.'s (1983) model (Figure 57), but the weight of the prograding aeolain dunes and liquefaction may have caused the strata to become deformed (Jones, 1972). The facies is similar to the lower shoreline sand (Figure 58) of the Minnelusa Formation as interpreted by Fryberger (1984). Another possibility is that the water was very shallow (intertidal) and sand was blown onto the marine flooded surface. The evaporitic environment would bind the sand. During exposed conditions the evaporites would expand and deform the strata. The long carbonate clasts associated with these lower deformed sandstone may have originated during intermittent exposure of the intertidal flats and incorporated as a lag deposit. This "drying-upward" sequence is common in other aeolian deposits (Kocurek, 1981) and may be further substantiated by deposition of salt ridge structures of facies U.

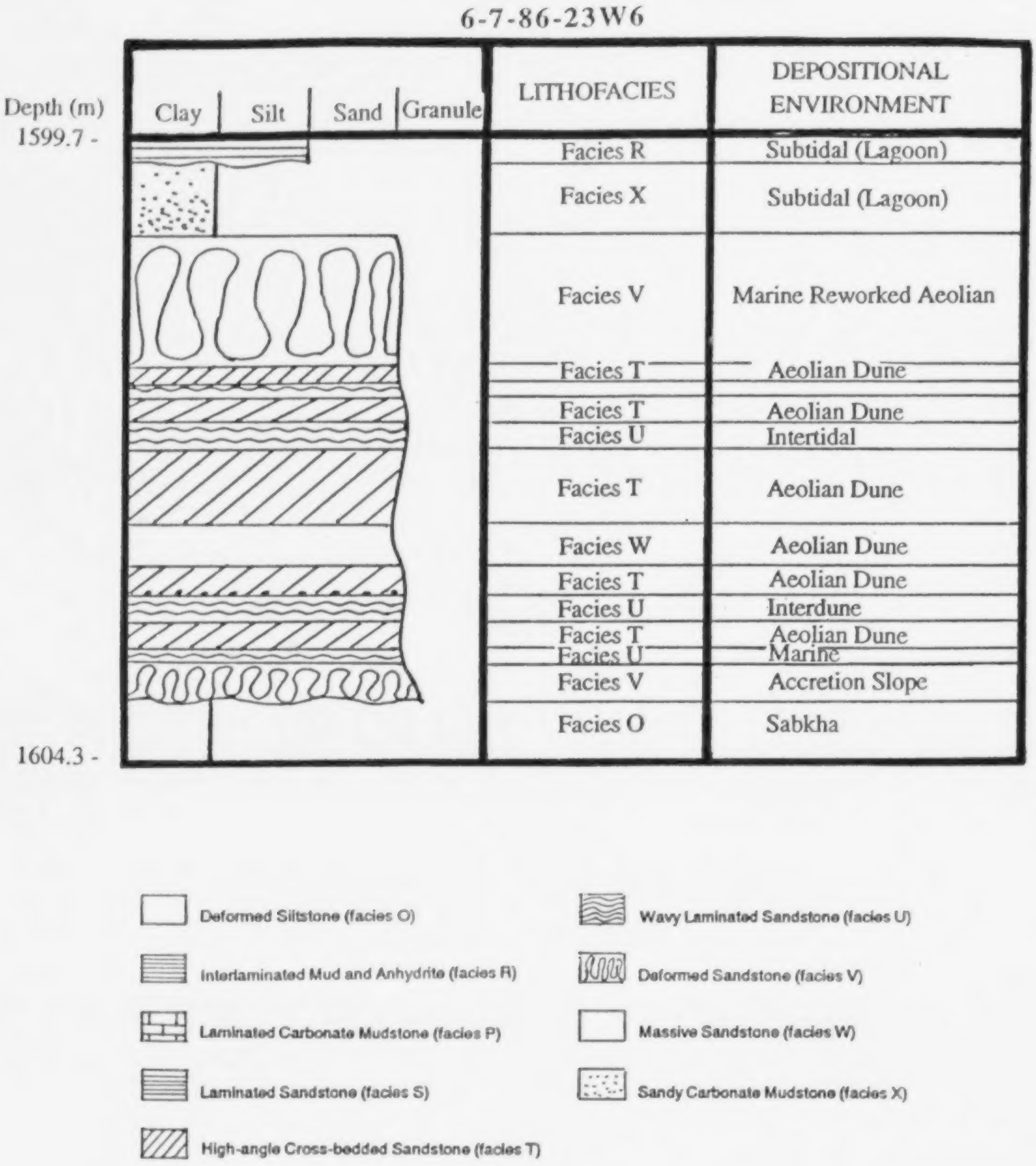

6-7-86-23W6
Depth (m)
1599.7 -
1604.3 -
Clay
Silt
Sand
Granule
LITHOFACIES
DEPOSITIONAL ENVIRONMENT
Facies R
Subtidal (Lagoon)
Facies X
Subtidal (Lagoon)
Facies V
Marine Reworked Aeolian
Facies T
Aeolian Dune
Facies T
Aeolian Dune
Facies U
Intertidal
Facies T
Aeolian Dune
Facies W
Aeolian Dune
Facies T
Aeolian Dune
Facies U
Interdune
Facies T
Aeolian Dune
Facies U
Marine
Facies V
Accretion Slope
Facies O
Sabkha
Deformed Siltstone (facies O)
Interlaminated Mud and Anhydrite (facies R)
Laminated Carbonate Mudstone (facies P)
Laminated Sandstone (facies S)
High-angle Cross-bedded Sandstone (facies T)
Wavy Laminated Sandstone (facies U)
Deformed Sandstone (facies V)
Massive Sandstone (facies W)
Sandy Carbonate Mudstone (facies X)

Figure 55. Sedimentary sequence of the lithofacies of the Inga Sandstone at well location 6-7-86-23W6 including an interpreted sedimentologic depositional environment.

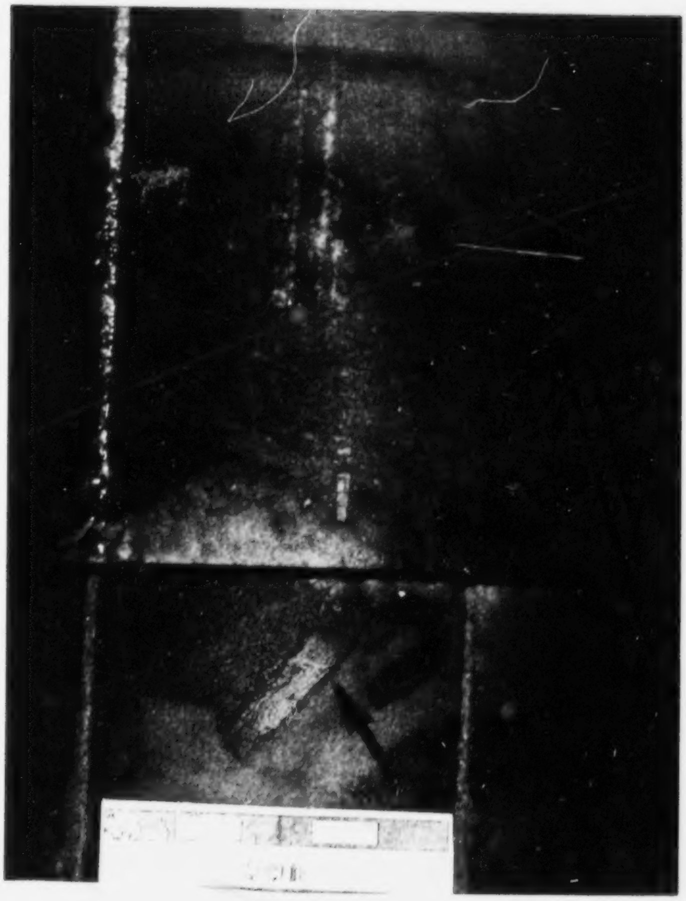


Plate 29. 1.0 to 3.0 cm long carbonate clasts (arrow) dispersed among deformed sandstone of facies V. The deformed sandstone is from the base of the Inga Sandstone. Well 15-12-88-24W6; 1607.9m.

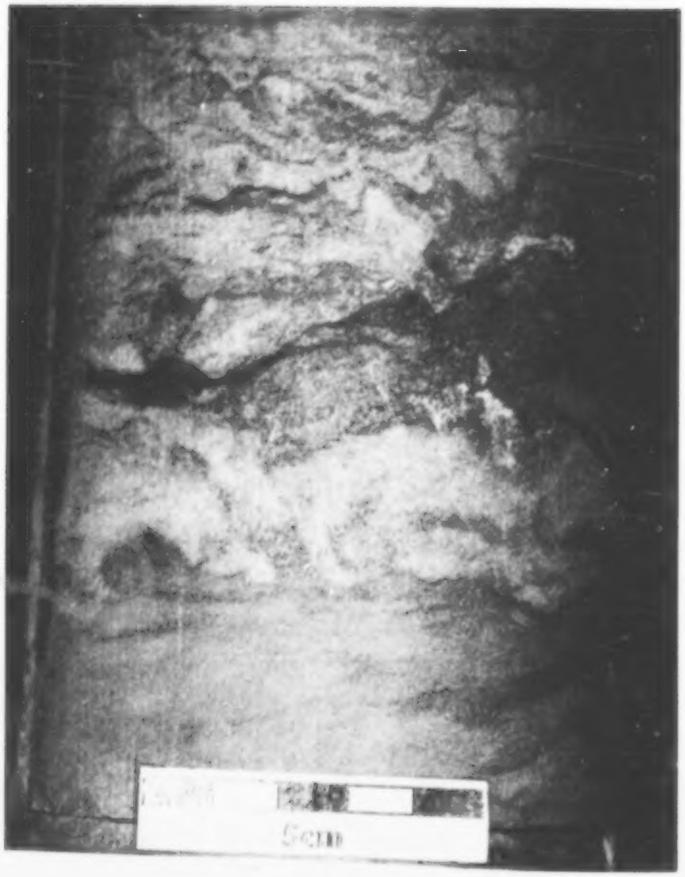


Plate 30. Deformed sandstone of facies V. The sandstone is from the top of the Inga Sandstone. Well 15-12-88-24W6; 1604.2m.

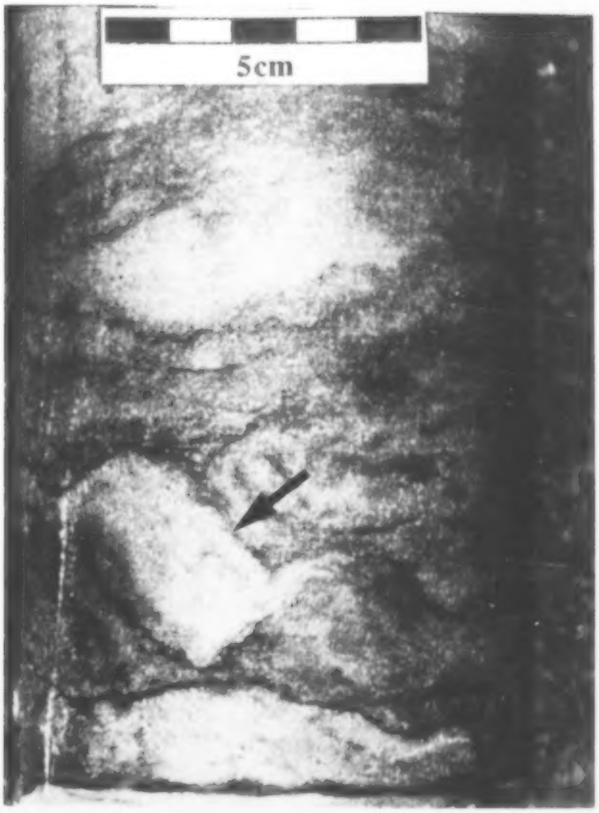


Plate 31. Deformed sandstone clasts in deformed sand matrix of facies V. The deformed clasts occur in the deformed sandstone at the top of the Inga Sandstone. Well D-28-J 94-A-12; 1639.6m.

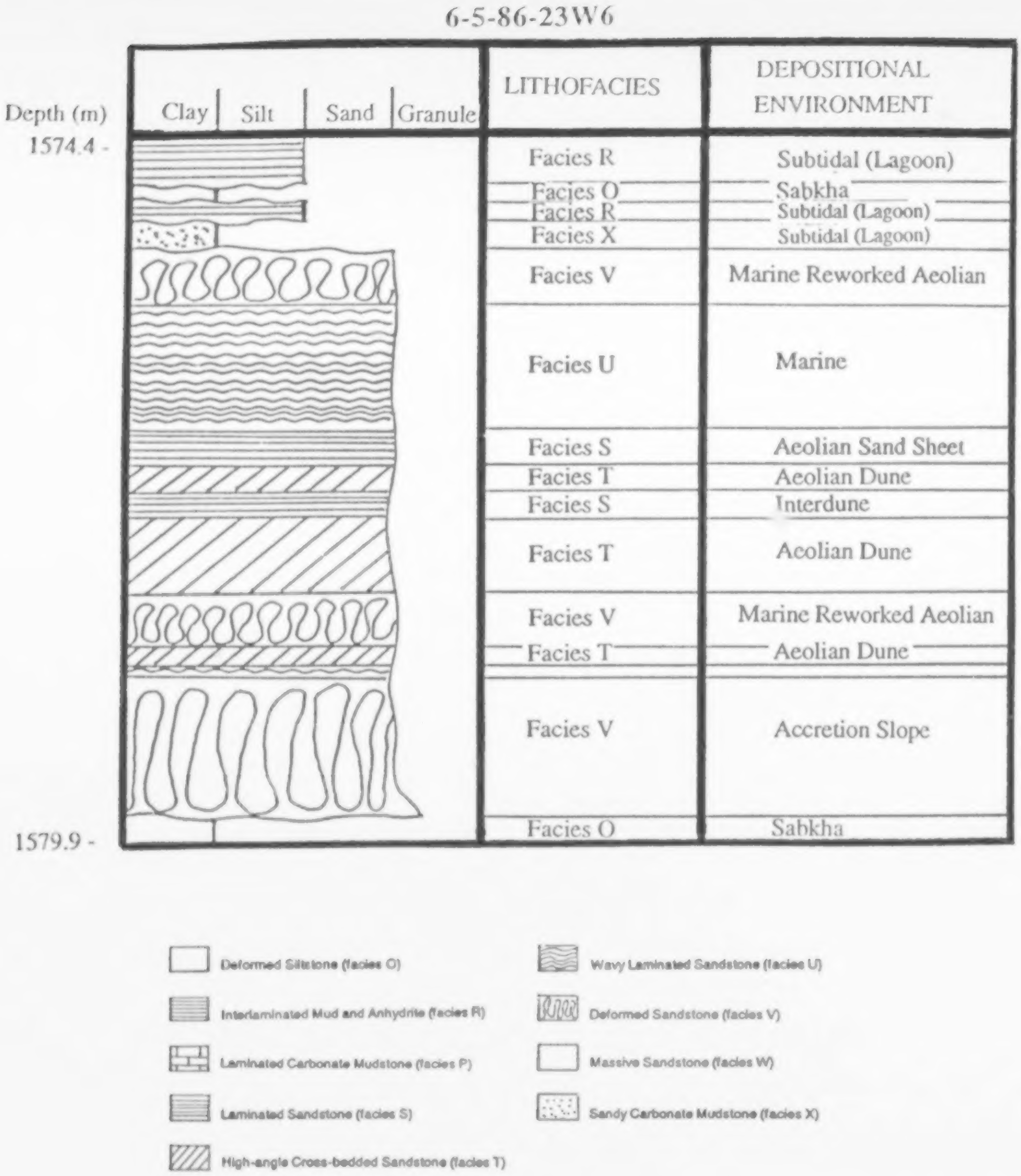

6-5-86-23W6
Depth (m)
Clay
Silt
Sand
Granule
LITHOFACIES
DEPOSITIONAL ENVIRONMENT
1574.4 -
Facies R
Subtidal (Lagoon)
Facies O
Sabkha
Facies R
Subtidal (Lagoon)
Facies X
Subtidal (Lagoon)
Facies V
Marine Reworked Aeolian
Facies U
Marine
Facies S
Aeolian Sand Sheet
Facies T
Aeolian Dune
Facies S
Interdune
Facies T
Aeolian Dune
Facies V
Marine Reworked Aeolian
Facies T
Aeolian Dune
Facies V
Accretion Slope
Facies O
Sabkha
1579.9 -
Deformed Siltstone (facies O)
Interlaminated Mud and Anhydrite (facies R)
Laminated Carbonate Mudstone (facies P)
Laminated Sandstone (facies S)
High-angle Cross-bedded Sandstone (facies T)
Wavy Laminated Sandstone (facies U)
Deformed Sandstone (facies V)
Massive Sandstone (facies W)
Sandy Carbonate Mudstone (facies X)

Figure 56. Sedimentary sequence of lithofacies of the Inga Sandstone at well location 6-5-86-23W6 including an interpreted sedimentologic depositional environment.

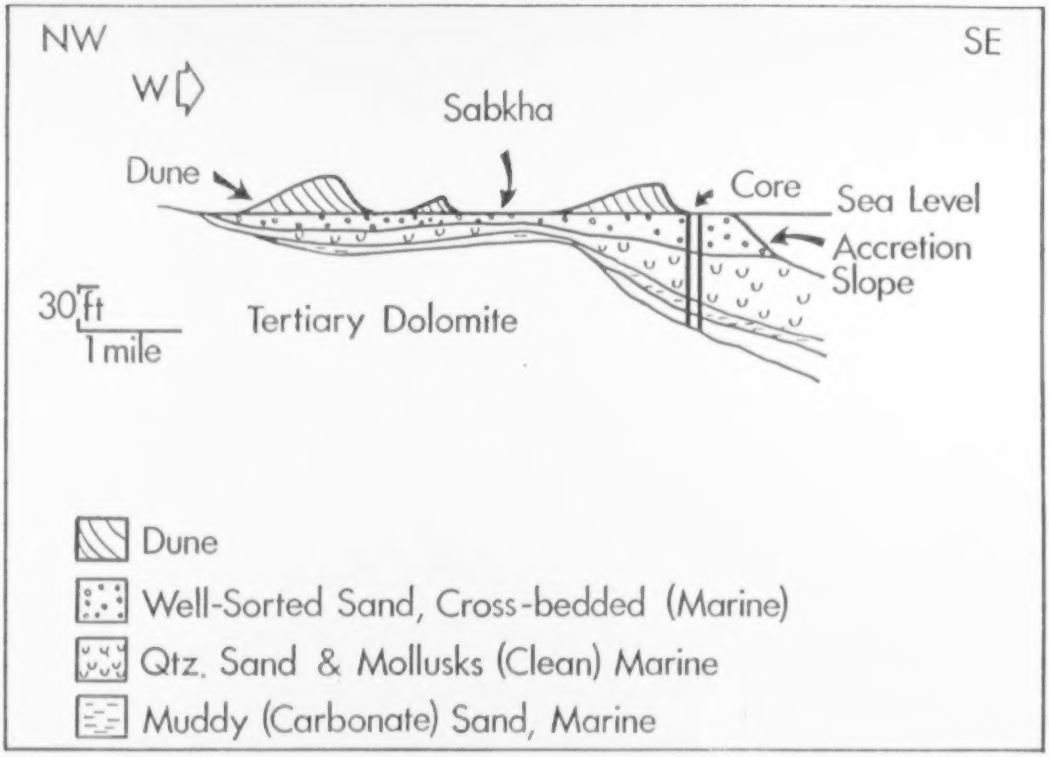

NW
SE
W
Sabkha
Dune
Core
Sea Level
Accretion
Slope
30 ft
1 mile
Tertiary Dolomite
Dune
Well-Sorted Sand, Cross-bedded (Marine)
Qtz. Sand & Mollusks (Clean) Marine
Muddy (Carbonate) Sand, Marine

Figure 57. Stratigraphy of Umm Said sabkha (after Shinn, 1973) showing offshore thickening of marine deposits (accretion slope) beneath a modern seaward prograding sabkha (modified after Fryberger et al., 1983).

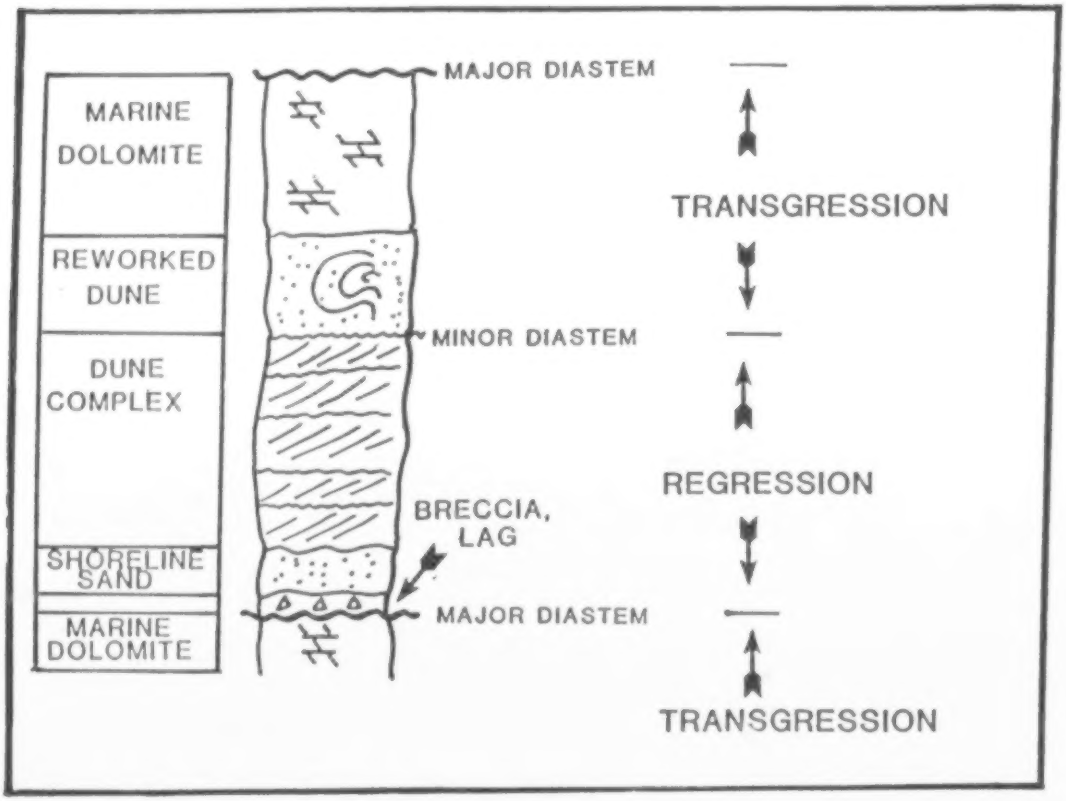

MARINE DOLOMITE
REWORKED DUNE
DUNE COMPLEX
SHORELINE SAND
MARINE DOLOMITE
MAJOR DIASTEM
MINOR DIASTEM
BRECCIA, LAG
MAJOR DIASTEM
TRANSGRESSION
REGRESSION
TRANSGRESSION

Figure 58. The idealized Minnelusa vertical sequence of lithologies, which typifies many of the cores studied by Fryberger, 1984. Note the shoreline sand at the base of the dune complex.

Deformation of sandstones deposited within the body of the Inga Sandstone (Figure 56) are interpreted to be caused by liquefaction of sand during marine flooding associated with a minor rise in sea level. The flooding undercuts the dunes causing slumping, which is immediately followed by liquefaction (Eschner and Kocurek, 1986). Rises in sea level were not significant enough to outpace aeolian sedimentation therefore, after the initial transgression, the progradation of dunes resumed and dominated the depositional site (Chan and Kocurek, 1988). The deformed sandstones in this situation are therefore interpreted as aeolian sands that have been reworked by a minor marine transgression. The positioning of overlying rippled, salt ridge structure and dune cross-bed sandstones verifies the return to aeolian deposition.

The deformed sandstone which caps the Inga Sandstone sequence (Figures 53, 54, 55 and 56) is interpreted to be the product of marine reworking of the aeolian sand during a major sea level rise (figure 58) which ultimately resulted in the termination of aeolian deposition. The sharp contact with the underlying facies may be the depth to which marine reworking occurred. The clasts of deformed sand (Plate 31) suggest that the sand may have been partially cemented prior to the transgression (Tewes and Loope, 1992). Evaporitic conditions at the time of deposition likely resulted in early cementation of the deformed sandstones (Fryberger et al., 1990).

That part of the Inga sequence which consists entirely of deformed sandstone (Figure 59) is located on the margins of the Inga reservoir. The fact that the whole sequence is deformed suggests that the entire aeolian portion of the Inga Sandstone in this area has been marine reworked. There are up to six transgressive events recorded in the thicker Inga Sandstone sequences (Figure 60). However there is no evidence of how many events reworked the marginal aeolian sands. Thus the completely deformed Inga Sandstone succession may have been: a) reworked during the final major transgression; or b) partially reworked during all six transgressive events. Facies V may be the equivalent to facies L of the Brown Hill section.

8.9.0 Facies W. Massive Sandstone

DESCRIPTION: Facies W consists of white to grey, lower-to upper-fine grained sandstone and is well sorted. The facies occurs as beds 3cm to 40cm thick. The sandstone is anhydrite cemented and does not display any sedimentary or biogenic structures. Facies W is occasionally oil stained. It occurs stratigraphically at the base of the Inga Sandstone or between high-angle cross-beds of facies T. No fossils were identified.

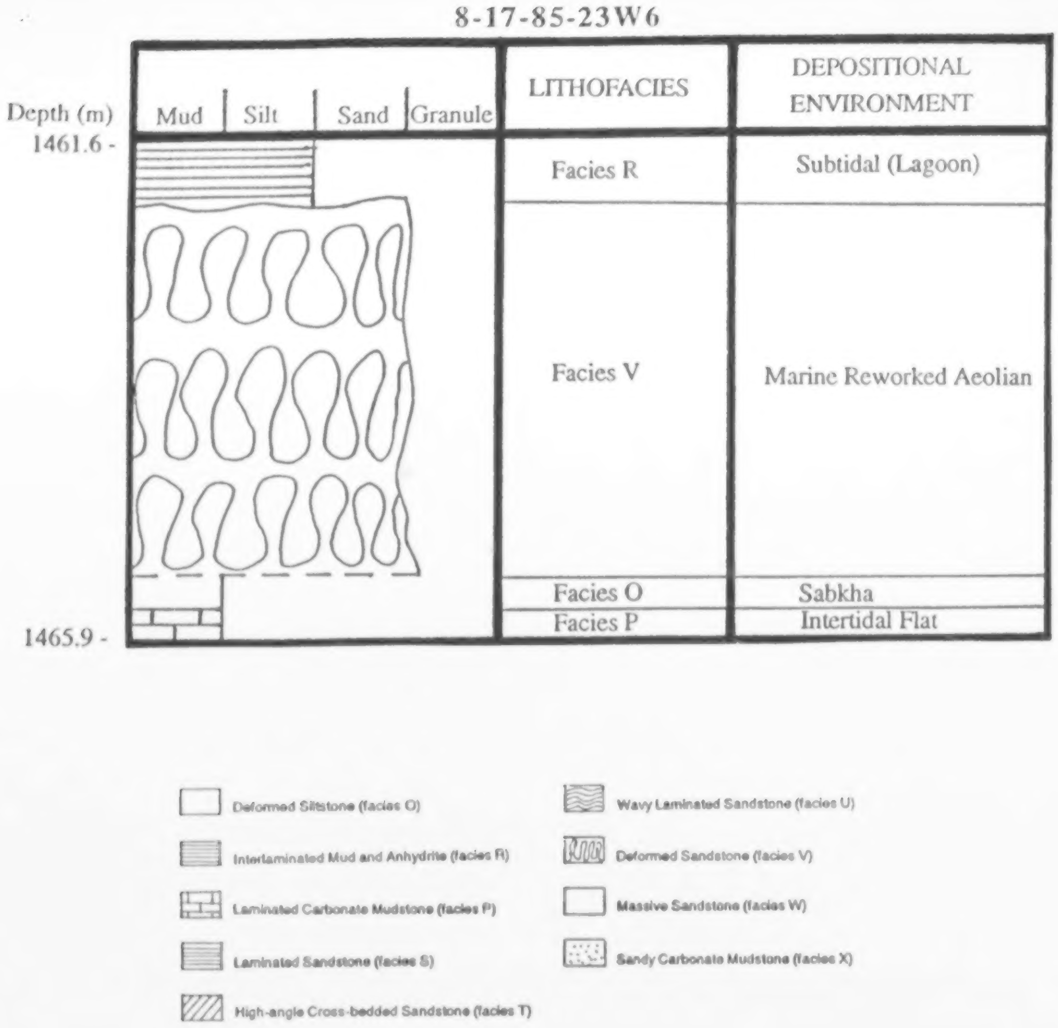

8-17-85-23W6
Depth (m)
Mud
Silt
Sand
Granule
LITHOFACIES
DEPOSITIONAL ENVIRONMENT
1461.6 -
Facies R
Subtidal (Lagoon)
Facies V
Marine Reworked Aeolian
Facies O
Sabkha
Facies P
Intertidal Flat
1465.9 -
Deformed Siltstone (facies O)
Interlaminated Mud and Anhydrite (facies R)
Laminated Carbonate Mudstone (facies P)
Laminated Sandstone (facies S)
High-angle Cross-bedded Sandstone (facies T)
Wavy Laminated Sandstone (facies U)
Deformed Sandstone (facies V)
Massive Sandstone (facies W)
Sandy Carbonate Mudstone (facies X)

Figure 59. Sedimentary sequence of lithofacies of the Inga Sandstone at well location 8-17-85-23W6 including an interpreted sedimentologic depositional environment.

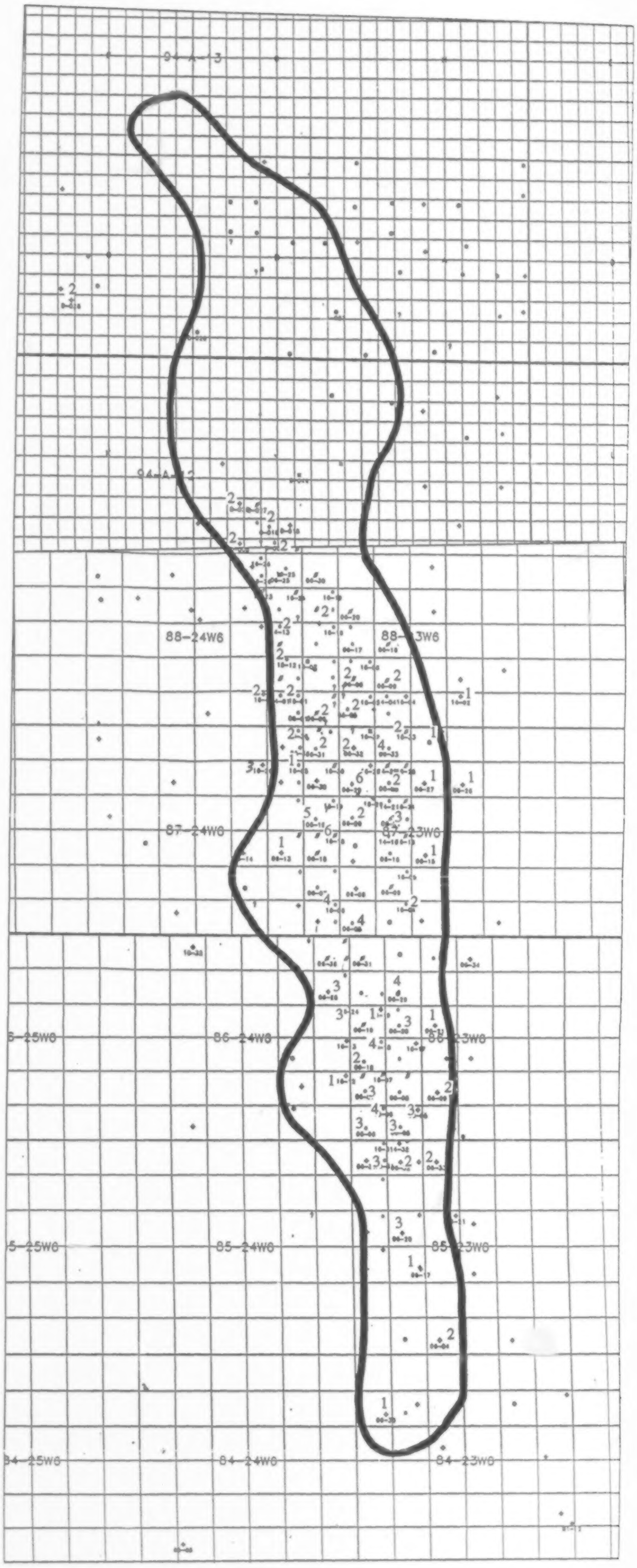

88-24W6
88-23W6
87-24W6
87-23W6
86-24W6
86-23W6
85-24W6
85-23W6
84-24W6
84-23W6

Figure 60. Map indicating the number of marine flooding events (deformed sandstones) within examined cores of the Inga Sandstone. Note that 1 indicates the entire Inga sequence is deformed.

INTERPRETATION: The massive sandstone is hard to interpret as sedimentary structures are absent. However, stratigraphic positioning along with porosities and permeabilities provide some insight into the depositional origin. The massive sandstones found at the bases (Figure 52) and tops of the Inga Sandstone are probably internally deformed just like other bases and tops of Inga cored sequences (Figures 53, 54, 55 and 56). The abundant cementation results in total loss of porosity and permeability frequently characteristic of the deformed sandstones (facies V).

The massive sandstone found between beds of high-angle cross-bedded sandstone (facies T) may originally have been cross-bedded (Figures 54 and 55). The porosities and permeabilities (chapter 10) of the two facies (T and W) are very similar providing further evidence of a similar origin. It is also possible that the massive sandstone may be aeolian grainfall strata. Grainfall strata leaves indistint fading laminations (Hunter, 1977) and cementation may have further obscured the structures leaving the facies massive in appearance. However, grainfall strata typically have lesser porosity and permeability values than sandflow strata (facies T) (Hunter, 1977). Facies W is absent at the Brown Hill section.

8.10.0 Facies X. Sandy Carbonate Mudstone

DESCRIPTION: The sandy mudstone consists of quartz sand floating in a carbonate mud matrix. The sand is lower-to upper-fine grained and occurs in beds 50 to 70cm thick. The facies is always positioned stratigraphically above the Inga Sandstone (Figures 52 and 54). The facies consists of 50% sand and 50% mud near the contact with the Inga Sandstone and changes to 20% sand and 80 % mud upwards. The contact with the Inga Sandstone is usually sharp with a thin (1 to 2mm) mudstone layer but is occasionally gradational. The facies is massive to convoluted like the deformed sandstone of facies V. No trace fossils were identified within the facies.

INTERPRETATION: Facies X is interpreted as the last phase of marine reworking of aeolian sands. The marine transgression reworks the uppermost parts of the aeolian dunes while at the same time deforming the top of the underlying dunes. The high-energy event subsides and the semi-cohesive sand which was removed by the transgression begins to settle on the planed off dune tops. During waning flow, the sand supply decreases reflecting in the decrease in sand upward through the facies (Figures 52, 53, 54, 55 and 56). The transgression is inferred by the overlying deposition of facies P and R.

9.0.0 INGA SANDSTONE DEPOSITIONAL HISTORY

The Inga Sandstone is deposited within a peritidal sequence similar to facies association 2 of the Brown Hill section (Figure 28). The lateral facies relationships are the same as those discussed for the Brown Hill section in chapter 5. The only differences are that the Inga reservoir sandstone is deposited further landward as indicated by the abundance of sabkha siltstones and rarity of subtidal limestones. Also present, which is lacking in the Brown Hill section, are the bedded anhydrites (Facies R).

9.1.0 Inga Sandstone Depositional Setting

The Charlie Lake Formation was deposited on a prograding low-gradient coastal plain frequently transgressed during minor (produces interbedding of marine and aeolian facies) and major (terminates erg deposition and deposits a new peritidal cycle) sea level rises. The arid environment of the coastal plain produces a thick and extensive salt encrusted surface which becomes deformed by haloturbation. The plain thickens by evaporite growth and adhesion of wind blown silt and sand onto the surface. Since the coastal plain had a low-gradient, any minor sea level rise could flood the entire coastal plain for many kilometres. The flooding ceases sabkha coastal plain deposition and produces subtidal and intertidal carbonate deposition. The thickness of the carbonate deposits reflects the depth of the flooding water body and the length of time before the water body disappears and is replaced by prograding coastal plain deposits.

The flooding events commonly resulted in generation of restricted water bodies. The hydrologic restriction may be produced by barrier-bar complexes (Roy, 1972), aeolian damming, or salt growth (Andreason, 1992). The restricted water body becomes supersaturated and produces evaporite crystals which settle from suspension to the bottom of the water producing laminated anhydrite deposits. As the water body evaporates, water depth decreases to total evaporation and the laminated anhydrites are subject to subaerial exposure. This is followed by deposition coastal plain siltstones.

If a sand source and wind conditions are favorable for aeolian transport and deposition, aeolian deposits may accumulate during deposition of a prograding coastal plain sequence. The Inga Sandstone is one of several aeolian erg deposits which formed during these coastal plain advances.

9.2.0 Inga Dune Types

The cored sequences from the Inga Sandstone (Figures 52, 53, 54, 55, 56 and 59) display sedimentary features similar to the dune features of the Brown Hill section (Figures 34, 35, 41 and 42). The dominant dune structure is high-angle cross-beds of grainflow origin (facies T). These structures are produced by sand avalanching down a slipface of an aeolian dune. Dune forms can contain one, two or more slipfaces migrating in different directions depending upon the dune morphology. Slipface directions in core can be determined from dip metre data and by good well control. This was not done for the Inga Sandstone cores therefore another method such as sedimentology will be applied. There is a lack of grainfall and wind ripple strata interbedded with grainflow strata common to bidirectional linear morphologies and multidirectional star morphologies. This suggests that the dunes were probably of unidirectional transverse or slightly crescentic morphologies similar to the types interpreted from the Brown Hill section.

Interdune deposits consist of horizontal laminated sandstone (facies S) and wavy bedded sandstone (facies U) and occur cyclically within the high-angle dune strata (facies T). The two interdune types differ in the moisture content of the interdune surface. The horizontal laminations are produced by migrating wind ripples on a dry interdune floor (Figure 53) while the wavy bedding is produced by sand adhering to a damp or wet interdune surface (Figure 55) caused by marine flooding during high tides or a high water table.

The wavy bedded interdunes are thin, lenticular, discontinuous deposits composed of anhydritic sandstones. These surfaces were periodically flooded and during drying cycles, salts formed a crust on the surface which expanded and caused the buckled ridges to form (Fryberger, et al., 1983). Interdune deposits of this type formed in depressions between dunes and their geometries are reflected by the interdunal topography (Figure 61). The geometry is characteristic of interdune areas belonging to crescentic dune types.

Interdunal surfaces which were not damp or wet due to flooding or a high water table are characterised by horizontal laminated sandstone. Since the surface is dry, wind ripples are not prevented from migrating. Each lamination is the product of a single wind ripple which has migrated over the surface.

9.3.0 Migration Pattern

The Inga reservoir is a north-south trending sandstone body that is orientated oblique to the paleo- Halfway shoreline. Dip metre data for other Charlie Lake aeolian sandstones indicate a southwest migration direction (Figure 16). Due to the lack of Inga Sandstone dip metre data, sedimentary structures and inferences will have to be used to determine the migration direction. Two sedimentary features are available which may indicate the migration pattern. The first is the number of deformed horizons within the aeolian sequence interpreted as a result of marine flooding (Figure 60). The Inga Sandstone sequence is always encased between deformed sandstone of facies V. The bottom

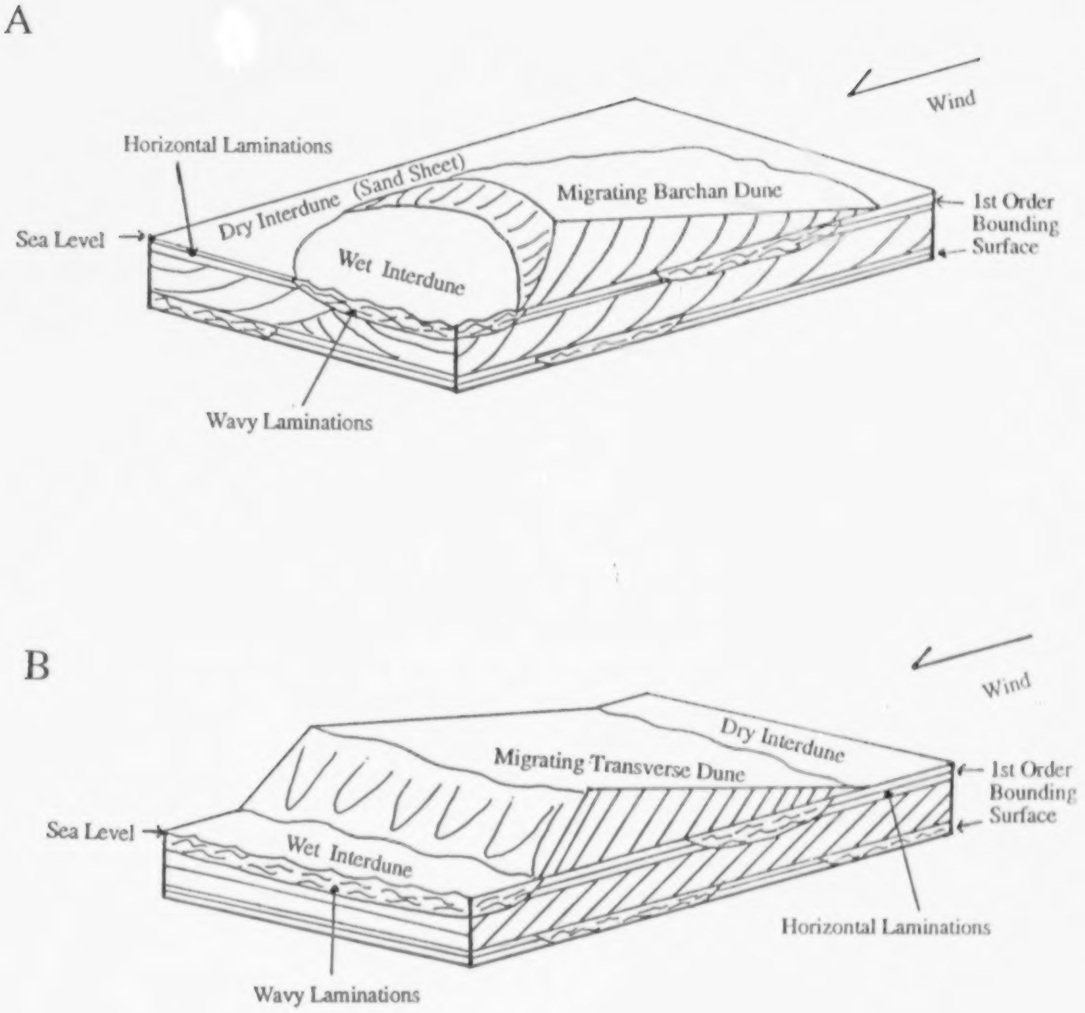

A
Wind
Horizontal Laminations
Dry Interdune (Sand Sheet)
Migrating Barchan Dune
Sea Level
Wet Interdune
1st Order Bounding Surface
Wavy Laminations
B
Wind
Dry Interdune
Migrating Transverse Dune
Sea Level
Wet Interdune
1st Order Bounding Surface
Horizontal Laminations
Wavy Laminations

Figure 61. Schematic diagrams displaying origin of tightly cemented sabkha/wet interdune/ bounding surfaces between dry interdune surfaces for migrating dunes of (A) barchan and (B) transverse forms.

deformed sandstone is interpreted as the accretion slope (Figure 57) produced by seaward prograding ergs (Fryberger, et al., 1983). This means that the erg is migrating towards the shoreline, so if the shoreline can be found, a likely erg migration direction can be inferred. Since all minor sea level rises are not expected to flood the entire erg system, the seaward margin of the erg should contain more flooding events in the Inga sequence than the upwind or landward margin of the erg. Strata of the south-southwestern margin of the reservoir indicate up to six flooding events while strata of the north-northeast margin of the reservoir indicates that it has never been cyclically flooded. This suggests an erg migration direction anywhere towards the south-southwest.

The second sedimentary feature that may suggest migration direction or at least the shoreline orientation is the basal contact of the Inga Sandstone. The Inga sequences in the north of the reservoir have an erosional contact with abundant rip-up clasts (Plate 29) while the contacts towards the south of the reservoir are gradational with a sandy mud grading upward into a deformed sandstone. The rip-up clasts suggest that the aeolian prograding surface was subaerially exposed while the prograding surface to the south was damp or wet probably due to the proximity to the coastline.

It appears that the crescentic dunes that make up the Inga Sandstone are prograding offshore towards the south-southwest (?). Dunes migrated across the coastal plain until they reached the back-barrier lagoon. Once at the lagoon, aeolian processes filled the shallow water body creating an accretion slope on which following dunes continued to prograde offshore. As dunes migrate they produce a hierarchy of bounding surfaces (Brookfield, 1977). The lack of second-order surfaces implies that draas were not formed and migration consisted just of simple crescentic dune forms (Kocurek, 1991). The climbing nature of the migrating dunes produces a sequence of stacked cross-beds separated by bounding surfaces. The bounding surfaces represent the interdune areas between each migrating dune and can be: a) featureless, b) marked by lag deposits, or c) consist of horizontal wind ripple strata (facies S) or siliclastic sabkha strata (facies U). The dunes will continue to migrate until the sand supply is diminished or until a major rise in sea level occurs.

The margins of the Inga reservoir are dominated by low angle to horizontal wind ripple strata (facies S). This lithofacies is typical of sand sheet deposits which are located on the margins of modern ergs. Sand sheet deposits tend to accumulate on erg margins because the sand supply in this part of the erg is not sufficient to produce dunes. Because the sand sheets are thin, broad low gradient deposits, they are easily reworked by marine sea level rises and highly unpreservable under these conditions. The sand sheet may be represented as a completely deformed Inga cored sequence (Figure 59).

9.4.0 Inga Erg Termination

The termination of the Inga erg occurred as a result of the same conditions which terminated erg deposition in the Brown Hill section. In a coastal marine setting, the erg will be affected by any sea level rise. The water-laid deposits within the Inga cored sequences may result from storm or tide influenced marine flooding and groundwater recharge (Eschner and Kocurek, 1986). If the rise is rapid enough, the water may bevel and rework the tops of the dunes. As long as there is a strong and constant sand supply to the erg, dune migration will overcome a minor sea level rise and reoccuppy the flooded plain. The result is a sequence of dune cross-beds (facies T) interbedded (Figure 56) with marine deformed sandstones (facies V).

If the sand supply becomes deficient, followed by a major sea level rise, the erg advance will be thwarted and marine deposition will dominate. If the rise is rapid and associated with susstantial wave reworking, wave processes will rework and plane off the tops of the dunes leaving dune cross-bedded sandstone capped by marine liquified sandstone. Sand trapped in the once turbulent flow will then settle passively with marine mud (facies X) on top of the planar reworked dune surface. During the next regressive event coastal plain deposits will prograde over marine deposits, in which the advancement of another erg may occur.

10.0.0 RESERVOIR CHARACTERISTICS OF THE INGA SANDSTONE

The Inga reservoir is a linear sand body with the reservoir production from the centre of the sand body. The centre of the sand body attains thicknesses of 5m while the margins attain thicknesses just over 1m (Figure 62). The producing area does not consist of one particular facies type but is made of several facies as a result of the different depositional processes and environments associated with coastal aeolian dunes.

10.1.0 Reservoir Lithofacies

Reservoir facies are lithofacies of the Inga Sandstone which possess permeabilities of or greater than 0.2 millidarcies and porosities of or greater than 5 percent. Based on this criteria there are five reservoir lithofacies each with their own reservoir properties and characteristics inherent from their process of deposition.

10.1.1 High-angle Cross-bedded Sandstone

The high-angle cross-bedded sandstone (facies T) is produced by sand avalanching down the slipfaces of migrating aeolian dunes. Sand grains in the grainflow deposits come from the wide grain size population associated with migrating wind ripples on the stoss slope of the dune. When the ripples reach the crest, the finer grains in saltation overrun the dune crest and form grainfall strata. The coarser grains arrive at the crest by creep, and then avalanche when the crest becomes over-steepened. This process involves a loose grain packing which results in the highest permeabilties and porosities (45%) in aeolian deposited strata (Hunter, 1977). The best quality reservoir facies of the Inga Sandstone are of this type with permeabilities ranging from 0md to 912md (Figure 63) and averaging 201md while porosities range from 0% to 25.3% (Figure 64) and averaging 15.4%. Grainfall strata is not preserved in the Inga dune deposits because the grainflow events remove the grainfall deposits by the erosive action during avalanching.

The depositional process also creates directionally preferred permeabilitiess within the strata. Individual cross-bed laminae are typically a few millimeters in thickness but can extend for many metres along strike of the dune slipface. As the dune migrates, many fine and coarser layers are developed along the slipface due to grain segregation by shear sorting giving the dune numerous partial barriers to flow in the direction of wind transport. These barriers however are also of sand so they are still permeable. This produces directionally-perferred permeability (Figure 65) in dune deposits parallel to the strike of the dune (Krystinik, 1990).

10.1.2 Horizontally Laminated Sandstone

The horizontally laminated sandstones (facies S) are produced by migrating wind ripples.

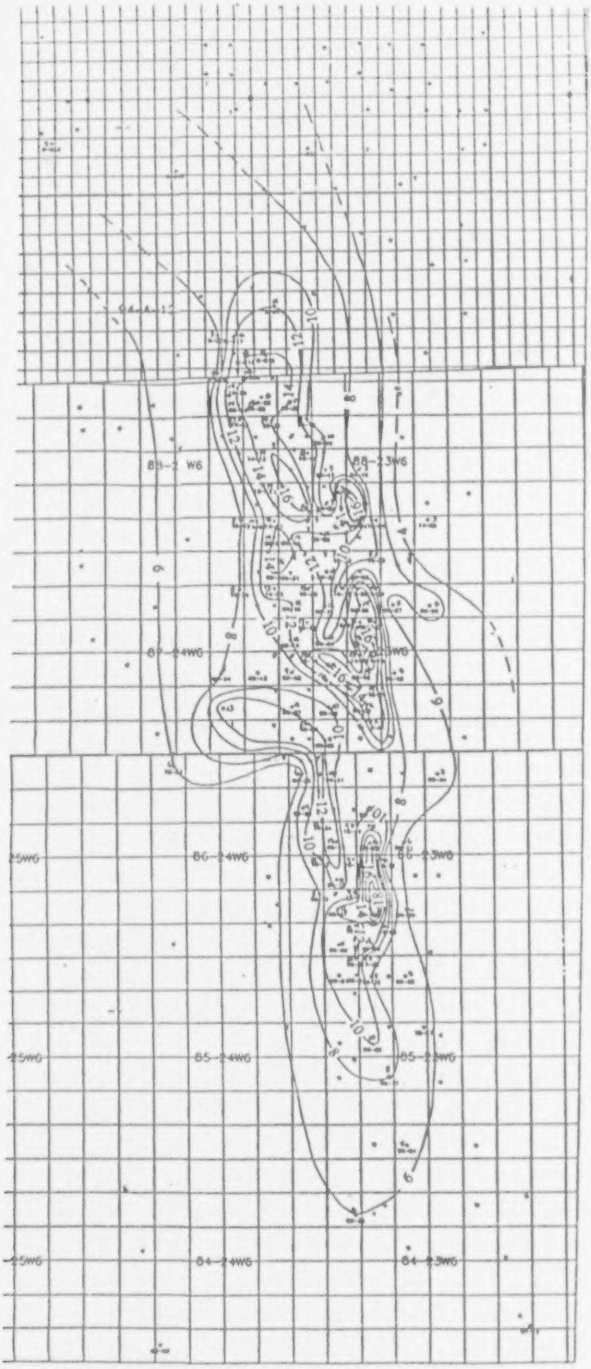

94-A-12
88-2 W6
88-23W6
87-24W6
W6
25W6
86-24W6
86-23W6
25W6
85-24W6
85-23W6
25W6
84-24W6
84-23W6
6
8
10
12
14
16
18

Figure 62. Isopach map of the Inga Sandstone Member (all sandstone facies) of the Triassic Charlie Lake Formation in the subsurface of northeastern British Columbia. Isopach intervals are 2.0Ft.

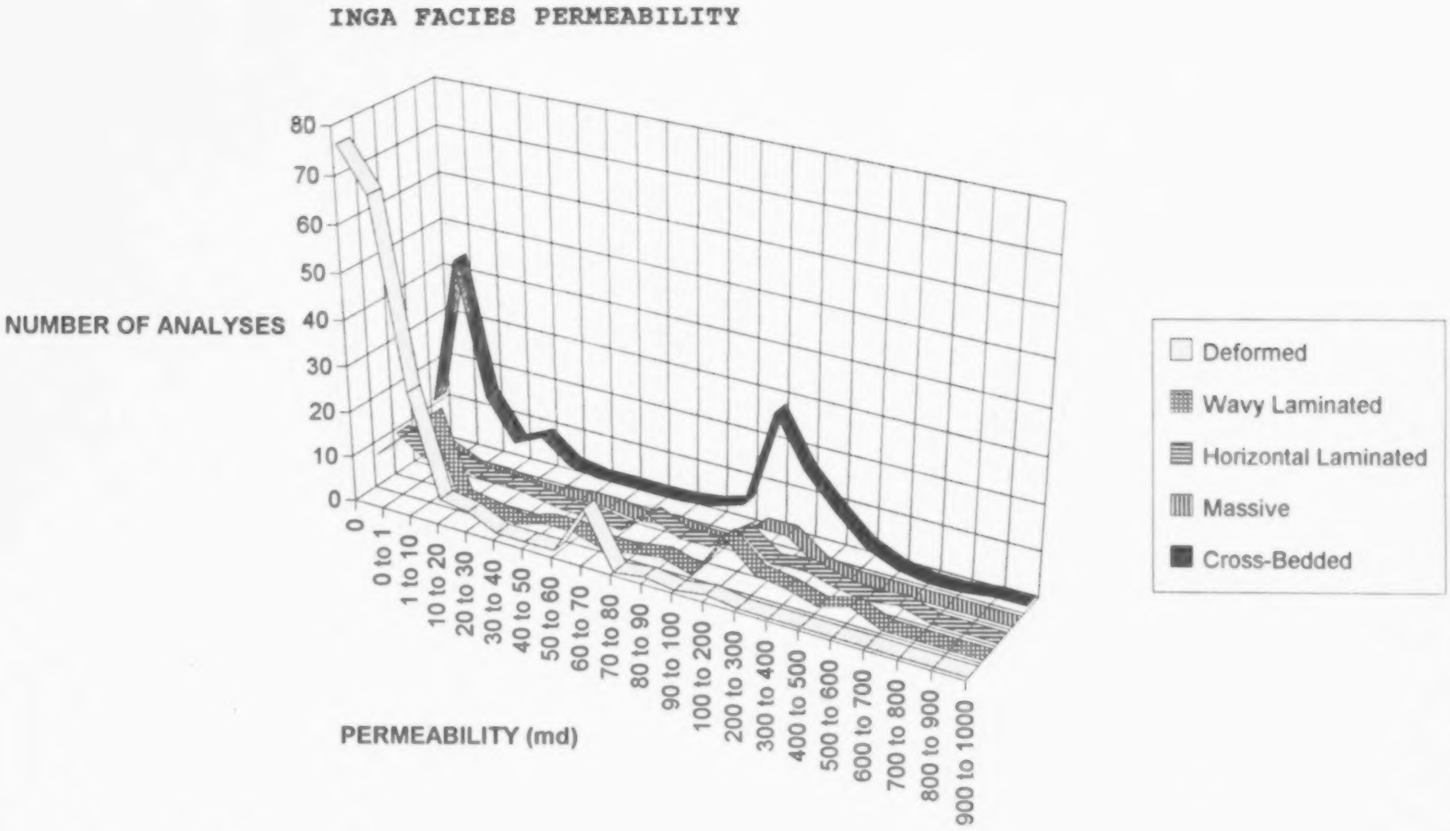


Figure 63. Frequency plot of the permeabilities of the various reservoir lithofacies within the Inga Sandstone of the Charlie Lake Formation.

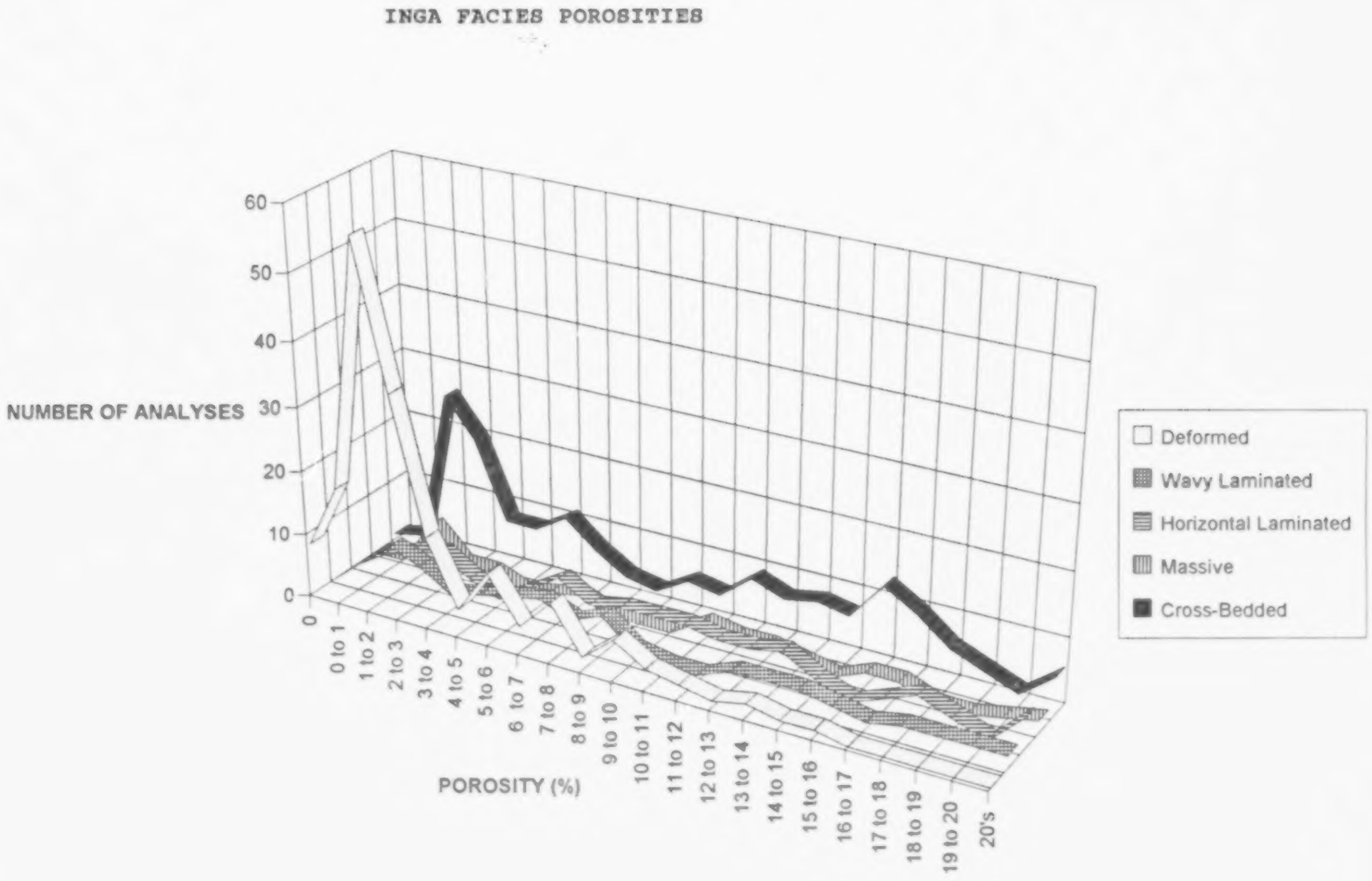


Figure 64. Frequency plot of the porosities of the various reservoir lithofacies within the Inga Sandstone of the Charlie Lake Formation.

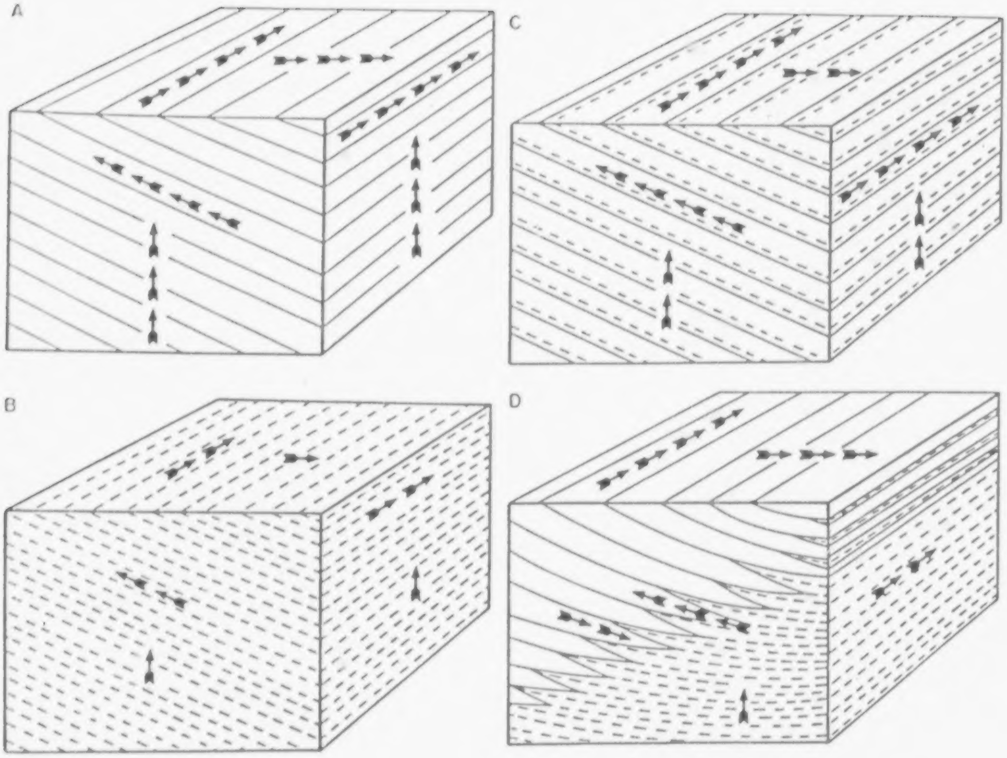


Figure 65. Common styles of cross-strata in aeolian sandstones. Directional permeability indicated by arrows; more arrows denote higher potential flow. (A) grainflow set. (B) wind-ripple set. (C) interlaminated grain-flow and wind-ripple set. (D) grainflow foresets toeing into wind-ripple bottomsets. (modified after, Chandler et al., 1989)

Wind ripples form during saltation in which fine sand and silt concentrate in the ripple troughs and are overlain by coarser grains in creep (Hunter, 1977). This produces thin laminations that are bimodally inverse graded. The ripple migration process produces relatively close packing of the grains into alternating sublayers of thin coarser grained sand separated by thin finer grained sands. As a result, wind ripples are the poorest quality of aeolian produced strata with an initial original porosity of 39% (Schenk, 1981). Because of the thin fine and coarse layering producing by migrating wind ripples, the preferred permeability direction is horizontal with a less vertical component (Figure 65).

The wind ripple strata (facies S) of the Inga Sandstone has wide rangeing permeability values of 0.0md to 630md with an average of 148md (Figure 63) and porosity values rangeing between 0.4% to 25.7% and averageing 9.8% (Figure 64). The low values are expected of the strata, however the high values are some of the best permeability and porosity values determined in the Inga Sandstone (Figure 66). These high values unfortunately are within thin interdune deposits (1 to 2cm) of wind ripple strata and therefore are not a major reservoir component of the Inga Sandstone.

The wind ripple strata are commonly interbedded with the more porous and permeable avalanche strata (facies T) and thus are interpreted as interdune deposits. Interdune deposits are associated with first order bounding surfaces which usually can be traced for kilometers along these surfaces (Kocurek, 1988). Since wind ripple produced interdune deposits are of lower permeability and porosity than the under and overlying avalanche strata they can act as barriers to fluid flow (Figure 67). However, the interdune deposits of the Inga Sandstone are laterally continuous (Figure 68) like other ancient aeolian sandstones and therefore, are not significant barriers to fluid migration.

10.1.3 Wavy Laminated Sandstone

The wavy laminated sandstones (facies U) are common to two depositional environments, however the porosity and permeability characteristics are the same. Facies U, when interbedded with high-angle cross-beds of facies T, are interpreted as sabkha deposits formed in interdune areas due to high water tables or high tidal flooding. The facies is also part of a drying upward sequence formed during shallowing and evaporation of marine flooding events.

Permeabilities and porosities are wide ranging with respective values of 0md to 544md, averaging 134md (Figure 63) and 0.6% to 22.7% averaging 6.9% (Figure 64). The preferred permeability direction in deposits of this type studied in other aeolian sandstones is about equal in the horizontal and vertical directions due to the associated homogeneous

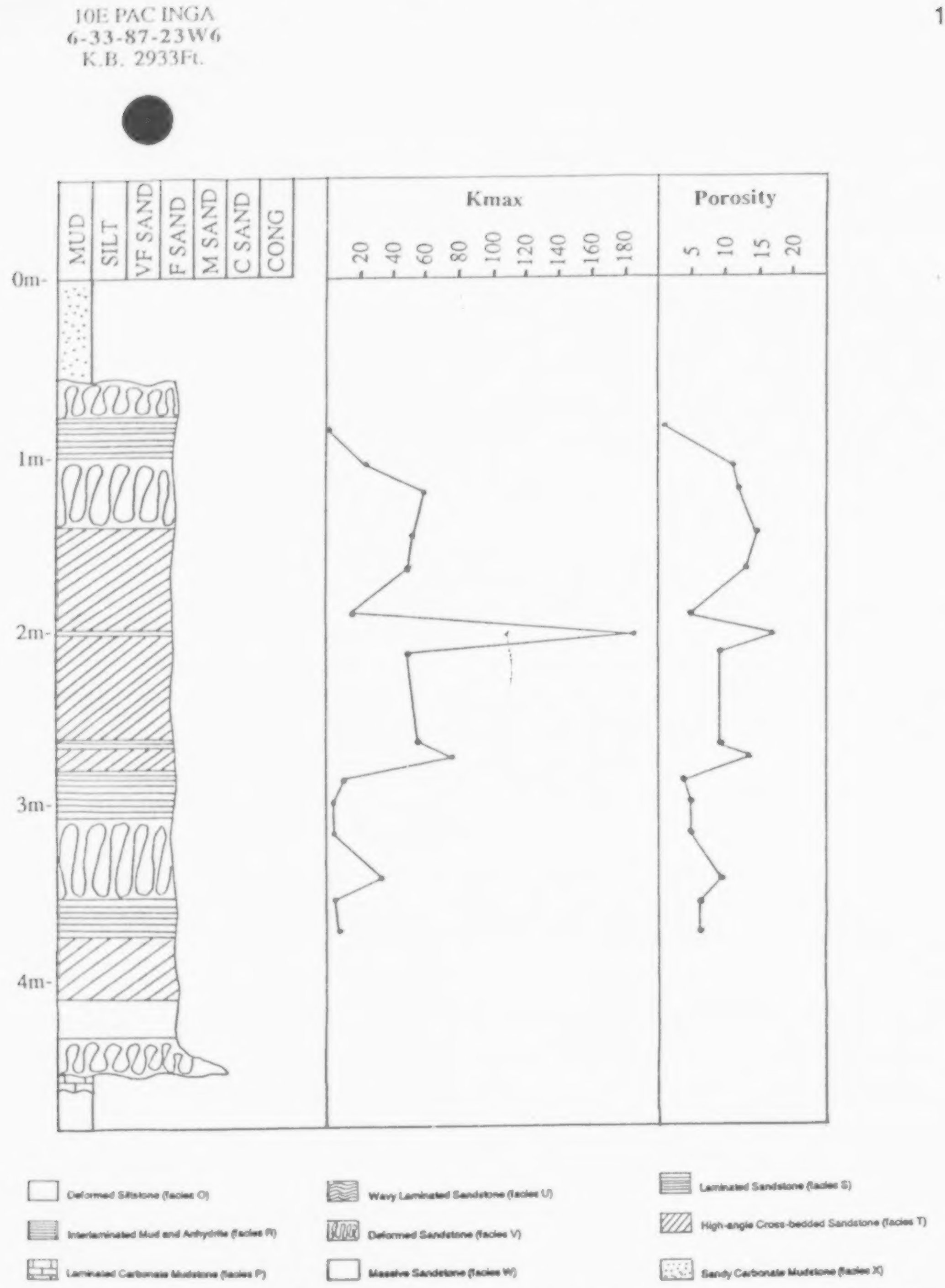


Figure 66. Reservoir permeabilities and porosities of the common sandstone lithofacies of the Inga Sandstone reservoir in well 6-33-87-23W6. Note the high values for the thin deposits of low-angle laminated sandstone (facies S).

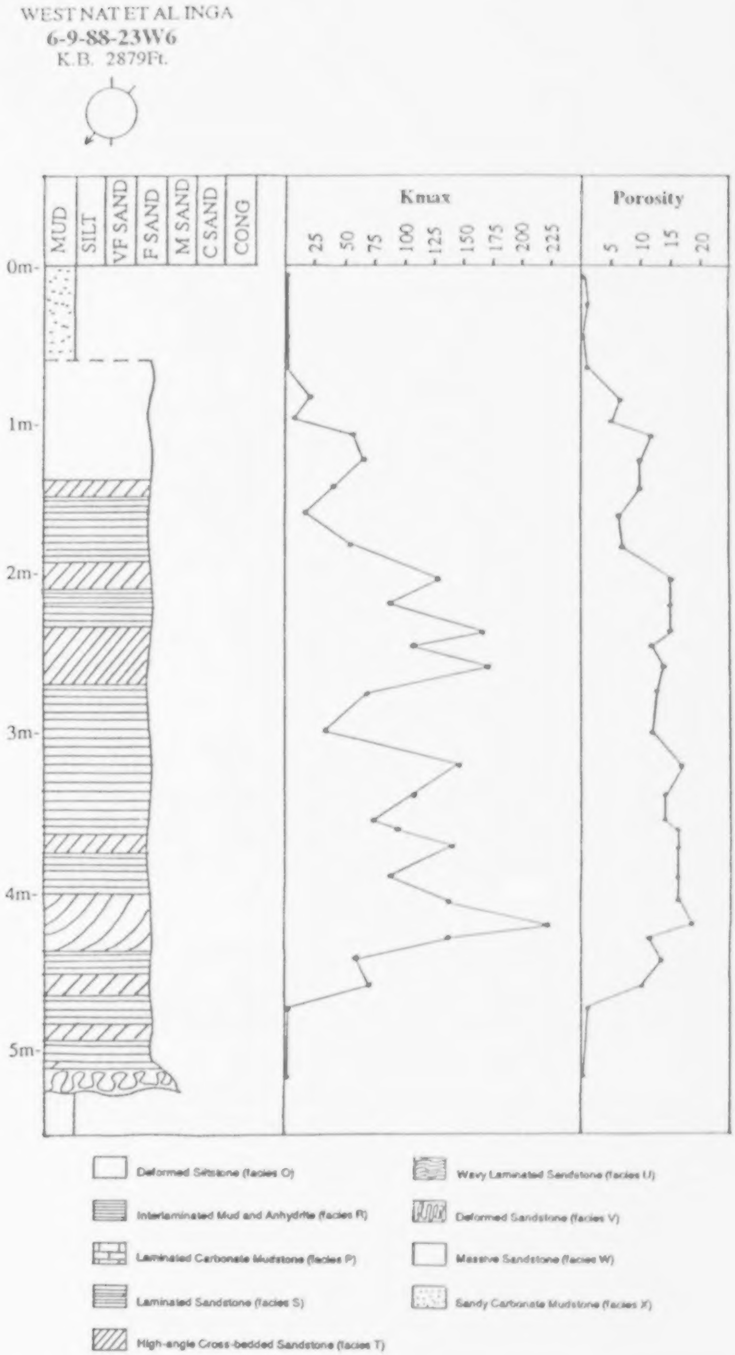


Figure 67. Reservoir permeabilities and porosities of the common sandstone lithofacies of the Inga Sandstone at well 6-9-88-23W6. Note the reduction in reservoir values between the high-angle cross-bedded strata (facies T) and the horizontally laminated strata (facies S).

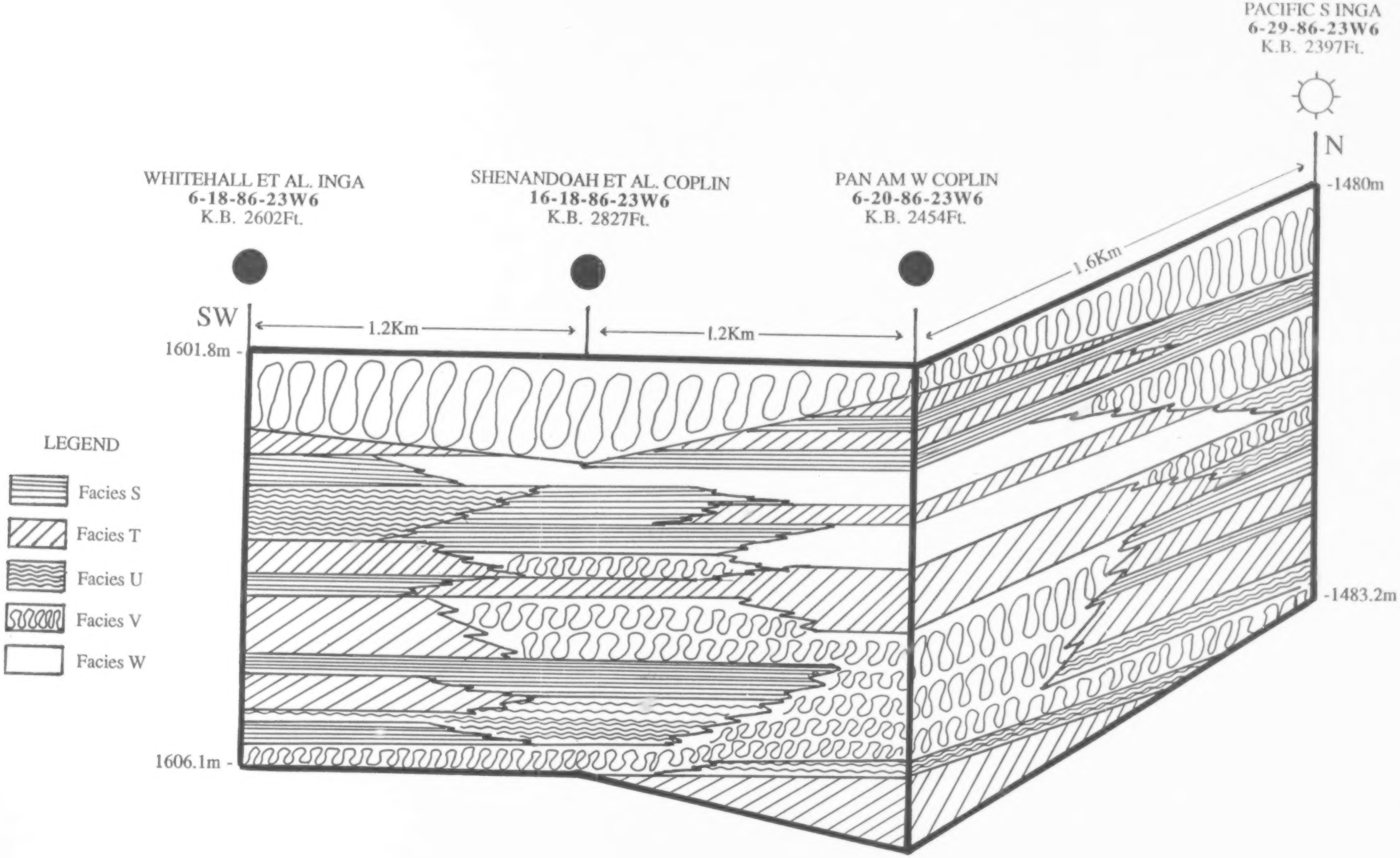

PACIFIC S INGA
6-29-86-23W6
K.B. 2397Ft.
N
-1480m
WHITEHALL ET AL. INGA
6-18-86-23W6
K.B. 2602Ft.
SHENANDOAH ET AL. COPLIN
16-18-86-23W6
K.B. 2827Ft.
PAN AM W COPLIN
6-20-86-23W6
K.B. 2454Ft.
1.6Km
SW
1.2Km
1.2Km
1601.8m
LEGEND
Facies S
Facies T
Facies U
Facies V
Facies W
-1483.2m
1606.1m

Figure 68. Correlation of the various sandstone lithofacies of the Inga Sandstone. Note that the facies typically lense out laterally from well to well creating local layering within the reservoir.

high cementation and salt growth in the facies (Krystinik, 1991).

The geometries of the wavy laminated sandstones associated with interdunes are determined by dune morphology. The dunes of the Inga are crescentic in form and therefore the interdune deposits are thin, lenticular and discontinuous (Figure 61). This is varified by the lateral discontinuity of the facies between wells (Figure 68). In addition, the facies may grade laterally into horizontally laminated interdune sandstones (Figure 61) of facies S in which the permeability and porosity values will increase (Andrews and Higgins, 1984). The interdune association of facies U between dune strata (facies T) creates baffles or barriers to fluid migration.

10.1.4 Deformed Sandstone

The deformed sandstones (facies V), produced by marine reworking of the aeolian dune deposits, contains permeabilities and porosities of reservoir quality that respectively range from 0md to 136md averaging 1md (Figure 63) and 0% to 15.7% and averaging 2.3% (Figure 64). Typically the facies has low reservoir permeability and porosity, probably due to cementation following marine reworking. As a result, the deformed sandstone is a possible barrier or baffle to fluid flowing from the higher quality reservoir rocks positioned above and below (Figure 69). The equal cementation of the sandstone creates no preferred permeability direction.

The deformed sandstones are laterally discontinuous between wells (Figure 68). The discontinuity of the sandstone suggests that the minor sea level rises never entirely flooded the dune field. Only portions of the field or the interdune lows were flooded, similar to the present day Padre Island dune field during seasonal storm events (Hummel and Kocurek, 1984).

10.1.5 Massive Sandstone

The massive sandstone is the least commonly occurring reservoir facies of the Inga Sandstone but possesses good reservoir properties. Permeabilities range from 0md to 335md and average 205md (Figure 63) while porosities vary from 1% to 20.2% and average 11.3% (Figure 64). The facies probably has a variety of origins depending upon its positioning in the cored sequence but this can not be determined as the facies is massive in appearance. However, its common occurrence between interdune deposits and its high permeabilities and porosities suggest a dune slipface origin similar to facies T (Figure 70).

The massive sandstones are not continuous from well to well (Figure 68). Adjacent wells usually lack the massive facies and contain abundant high-angle cross-bedded facies further

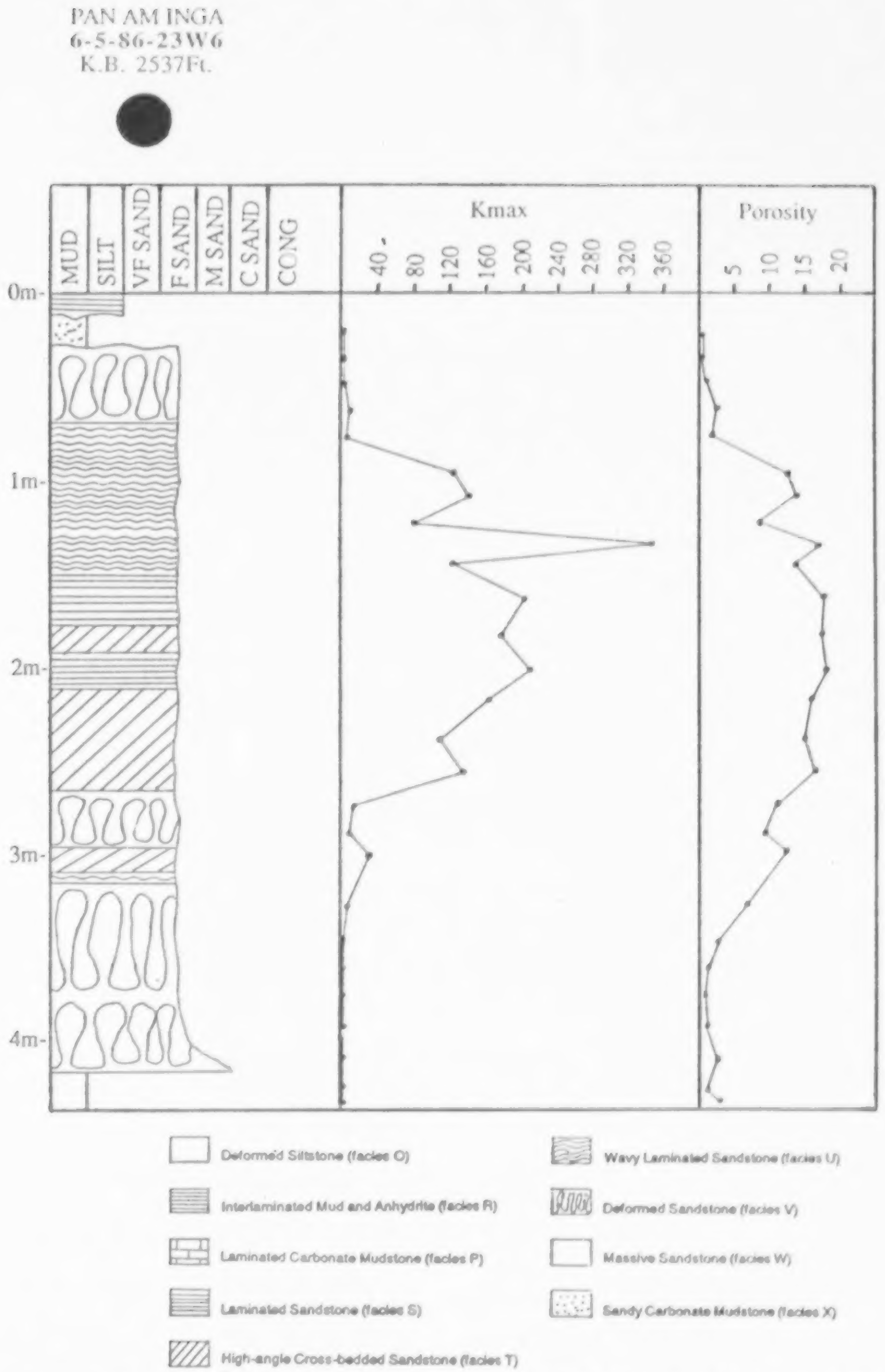


Figure 69. Reservoir permeabilities and porosities of the common sandstone lithofacies of the Inga Sandstone at well 6-5-86-23W6. Note the reduction in reservoir values when an internally deformed sandstone bed is present.

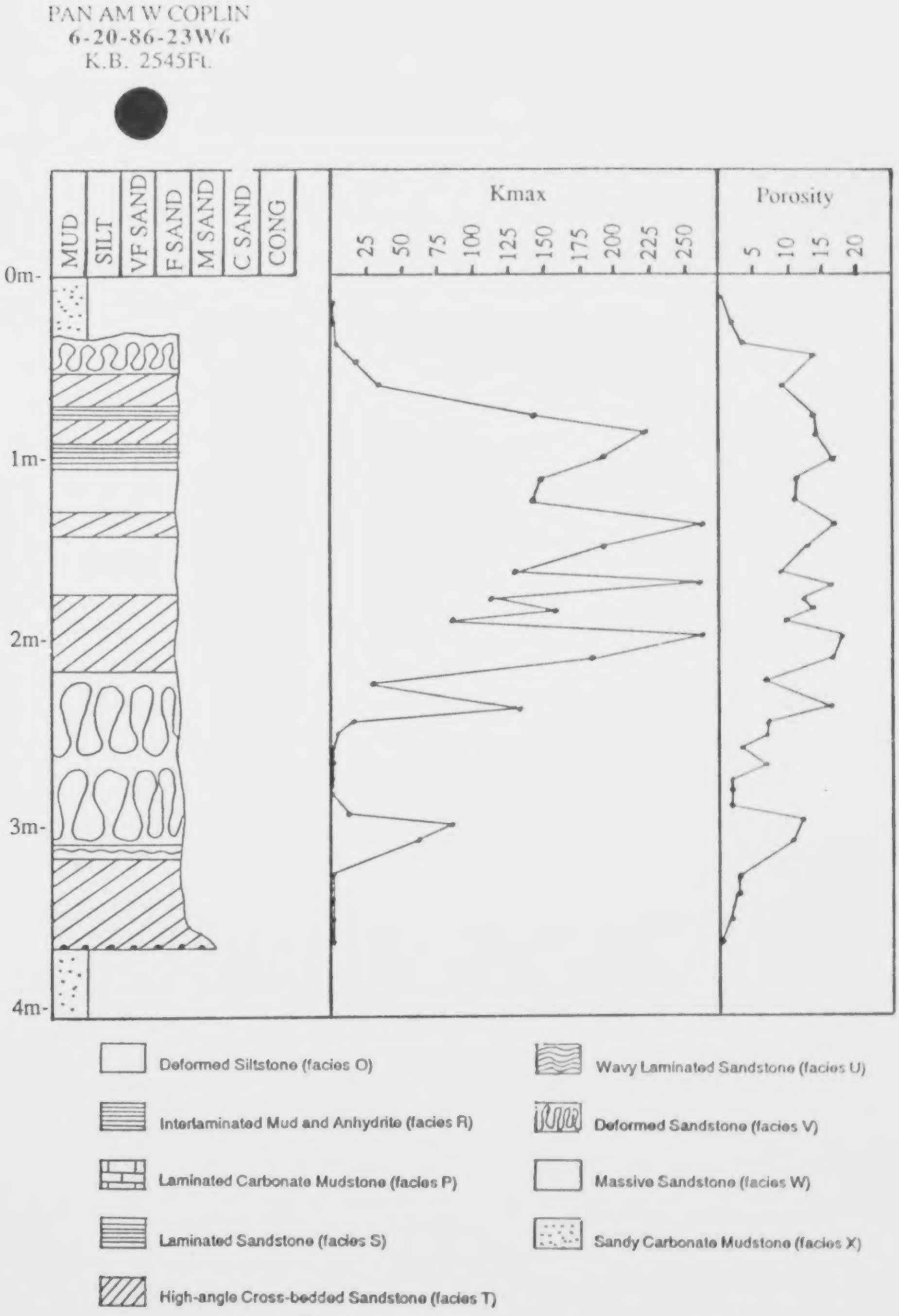


Figure 70. Reservoir permeabilities and porosities of common sandstone lithofacies of the Inga Sandstone in well 6-20-86-23W6. Note the high reservoir values for the massive sandstone lithofacies and how it compares with the high-angle cross-bedded sandstone lithofacies (facies T).

suggeting a similar origin. However, it is difficult to determine if the massive sandstones correlate to the high-angle crossbedded sandstones (facies T) or sandstones of a different facies. Thus the permeabilities and porosities of the massive facies may grade into sandstones possessing reservoir properties of facies T or into lower quality reservoir sandstones of facies S, U,V and W.

10.2.0 Inga Sandstone Cementation

Water plays a paramount role in the reservoir quality of aeolian deposits. In arid, coastal settings, marine incursions and evaporation can introduce cementing agents which lead to early cementation of the aeolian strata. Water is important because it transports the cementing ions from place to place. The emplacement of early cements by marine flooding, high water tables and desiccation of evaporitic deposits incorporated into the sand by wind, leads to the preservation of sedimentary structures and an open packing arrangement in the aeolian deposits (Fryberger, 1990). The marine flooding events (facies V) and arid setting displayed in the Inga core is the likely source of the abundant anhydrite cementation found in the sandstone.

Early cementation is commonly facies selective. Wind ripple strata is commonly the first to undergo cementation usually in the finer layers of the inverse graded produced lamina creating the distinctive pin striping associated with the facies. Salt cementation generally occurs early in the diagenetic history of the aeolian sandstone which may be removed later by groundwater during deeper burial creating a reservoir of porous and permeable sandstone. The early cementation is verified from the lithified sandstone clasts dispersed in the upper most deformed sandstone facies of the Inga (Plate 31). This suggests that the aeolian dunes were lithified prior to the final transgressive event which ripped up and incorporated the clasts during marine reworking.

Few simple diagenetic generalizations can be made of coastal aeolianites except that anhydrite and dolomite cementation usually is dominant, the aeolian sandstone is the reservoir target and the interdune, sabkha, and marine interbeds are seals. A diagenetic study of the sandstone will reveal an indepth understanding of the burial history of the sandstone.

10.3.0 Reservoir Layering and Compartmentalization

Migrating and climbing aeolian dunes produce first-order bounding surfaces which can extend for many km's. The vast interdune spaces between the migrating dunes and draas provide interdune deposits on these bounding surfaces. The interdune deposits can consist of a variety of environments including horizontal laminated sandstones produced by migrating wind ripples (facies S), wavy bedded sabkha sandstones (facies U), and non-depositional or lag deposits. Because these interdune deposits posess permeabilites and porosities of zero, or permeabilities and porosities less than the high-angle cross-bedded sandstones (facies T), which is the best quality reservoir facies, they may act as barriers or baffles to fluid flow. These barriers or baffles which can be laterally continuous may divide the sandstone body into reservoir layers or compartments.

The interdune deposits (facies S and U) and marine interbeds (facies V) of the Inga Sandstone however are not laterally continuous (Figure 68). As a result, the Inga Sandstone is one continuous reservoir body divided into facies compartments and is not layered from end to end into several sheet like reservoir bodies. The presence of interdune deposits however divides the reservoir locally into compartments causing baffles to fluid flow in the vertical and horizontal directions. These baffles plus the preferred directional permeability of the lithofacies (discussed in 10.1.0) creates a fluid flow model in which lateral flow is preferred over vertical flow.

10.4.0 Inga Fluid Flow Model

The change in vertical facies successions from well to well indicates that the sandstone facies of the Inga are laterally discontinuous. This creates local zones of contrasting permeability and porosity throughout the reservoir due to the different petrophysical and reservoir pressure characteristics of each sandstone lithofacies. As a result, fluids will migrate towards facies with greater permeabilities and porosities at the same time avoiding facies of lesser permeabilities and porosities (Figure 71).

Permeability directions in grainflow strata are generally very high in all directions with potentially greater flow along a grainflow stratum than across it. This property makes grainflow deposits the best reservoir strata in aeolian deposits. So it's convenient that the bulk of the Inga reservoir consists of this facies. As a result, fluid flows most easily within this strata type making grainflow strata pressure lows which cause fluids in pressure high facies (wind-ripple, deformed, massive, and wavy laminated sandstones) to leave and enter the more favourable low pressure area of the high-angle grainflow strata.

The permeabilities, porosities and preferred permeability directions of the stratification types (discussed in 10.1.0) of the Inga Sandstone create a hierarchy of reservoir-fluid preferred facies. The high-angle cross-bedded facies is the most effective facies for fluid flow followed by wind ripple laminated sandstones, massive sandstones, wavy laminated sandstones and finally deformed sandstones. This means that fluids low in the hierarchy will move to facies higher in the hierarchy, bypassing facies lower in the hierarchy. The

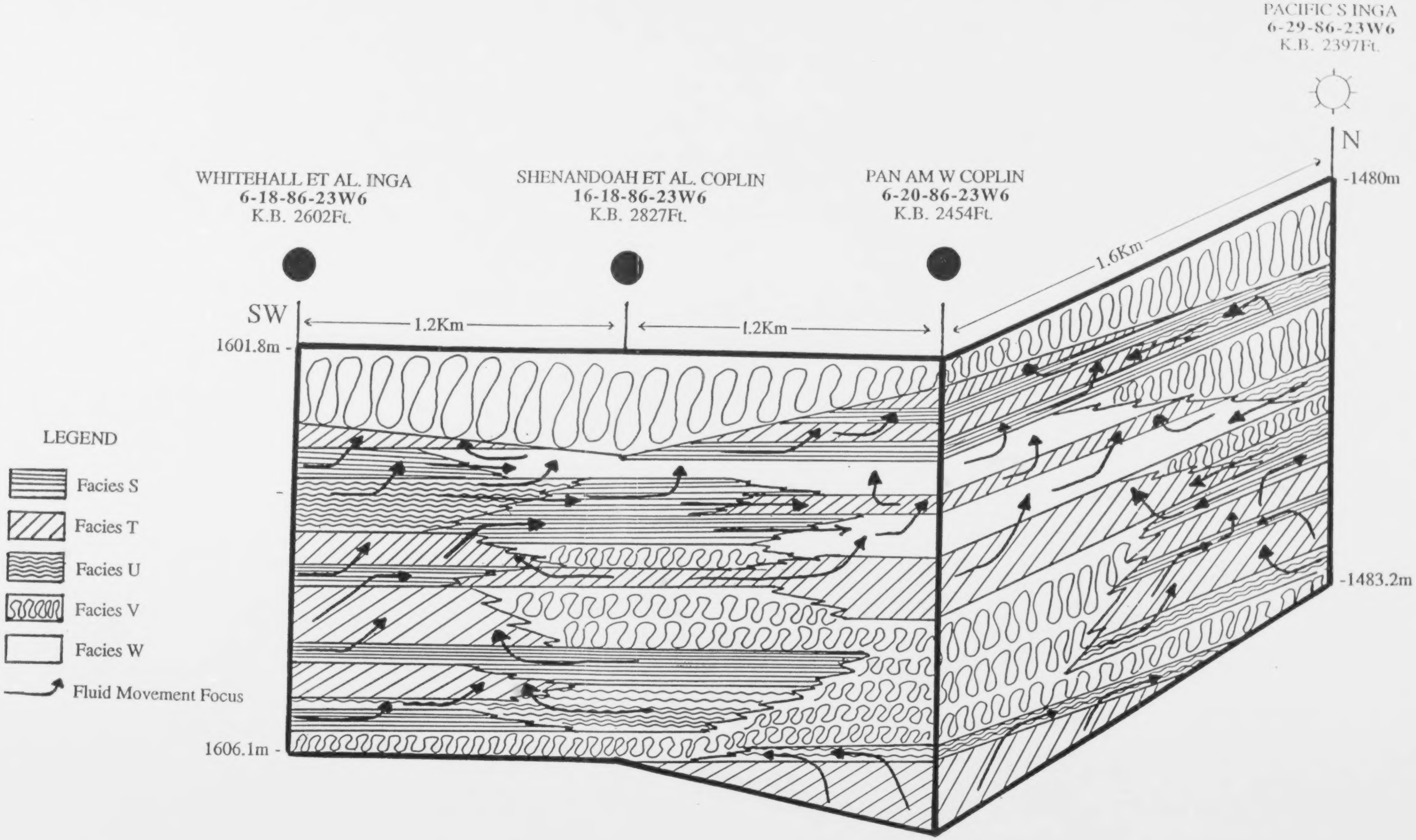

PACIFIC S INGA
6-29-86-23W6
K.B. 2397Ft.
N
-1480m
-1483.2m
1.6Km
WHITEHALL ET AL. INGA
6-18-86-23W6
K.B. 2602Ft.
SHENANDOAH ET AL. COPLIN
16-18-86-23W6
K.B. 2827Ft.
PAN AM W COPLIN
6-20-86-23W6
K.B. 2454Ft.
SW
1.2Km
1.2Km
1601.8m
1606.1m
LEGEND
Facies S
Facies T
Facies U
Facies V
Facies W
Fluid Movement Focus

Figure 71. Fluid flow through a portion of the aeolian Inga Sandstone reservoir based on relative permeability values of stratification types and bounding surfaces, assuming a vertical pressure field.

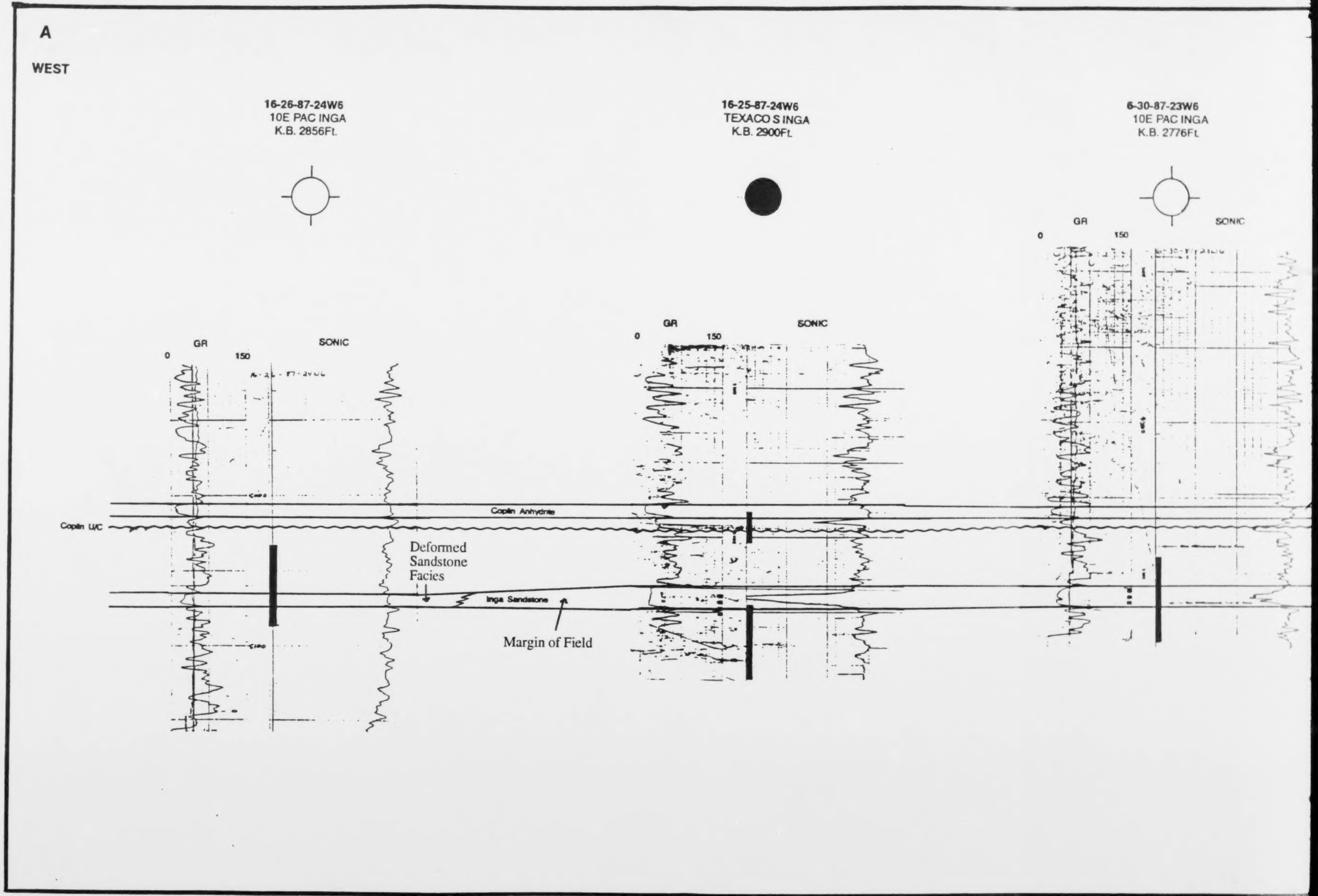
fluid remains within the high-angle crossbedded strata after it enters. The fluids are trapped within the reservoir by nonpermeable and nonporous seals of upper and lower deformed sandstone, anhydrites and carbonates which force the fluid to flow laterally within the Inga Sandstone reservoir. A fluid flow model of the Inga Sandstone is shown in figure 71.

10.5.0 Preservation of Inga Sandstone

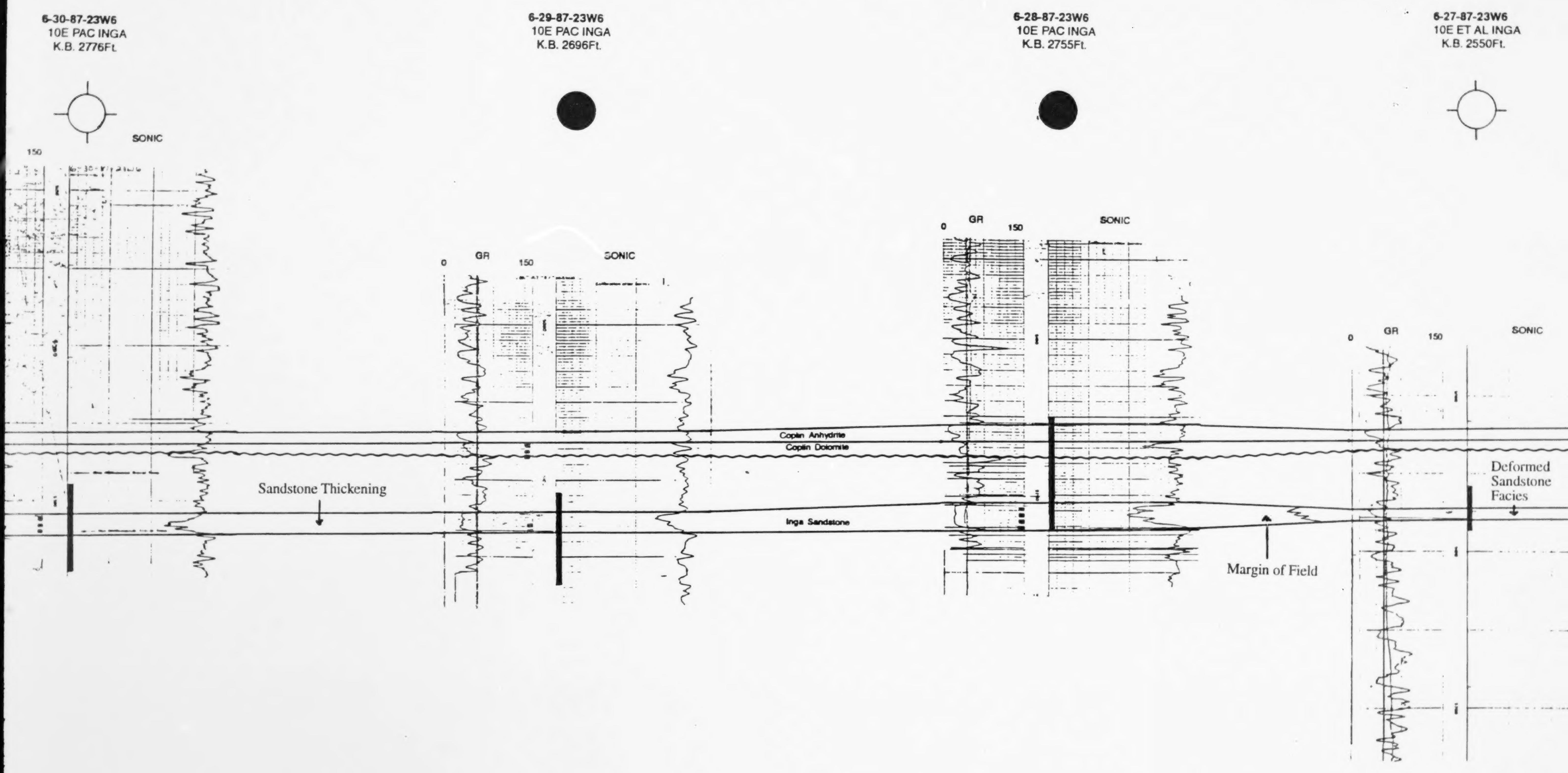
Preserved aeolian dunes are generally deposited in topographic basins (Wilson, 1973). The well studied coastal aeolian sandstones (Morgan, Cedar Mesa, Tensleep, White Rim, Coconino, Entrada) of the United States occupied the eastern portion of the Cordilleran miogeocline as a whole, but within smaller, discrete structural basins (Chan and Kocurek, 1988). The Inga Sandstone and the other aeolian sandstones of the Charlie Lake Formation are likely to be deposited within similar smaller basins associated with the Fort St. John graben complex. The Fort St. John graben system originated before Charlie Lake deposition but is believed to have been active through the Triassic period (Cant, 1988). The depth of the grabens may have been very shallow (few m's) and are outlined by the increases and decreases in thickness of the aeolian sandstones (Figure 72) (personal communication, Dave Robinson, 1992). The shallow depth of the grabens are also reflected by the thin aeolian deposits compared to the thicker American southwest aeolian deposits of the Cordilleran miogeocline. The aeolian sand that accumulates within the graben basin is thus thicker and becomes the reservoir within the sandstone. The graben acts as a trap for sand accumulation and as a possible shield for aeolian preservation within the graben from marine reworking during sea level rises (Figure 73).

The sandstone thick may also reflect partial preservation of dune topography. The margins of the Inga reservoir are thin and consist of completely marine reworked sandstone whereas only the top of the thicker central parts of the reservoir are reworked with aeolian sandstone preservation below (Figure 73). As the transgressions approach the dune field, they can more easily rework the thin erg margins than the entire central parts of the erg. This leaves a drapping of marine reworked sandstone over the non-reworked aeolian dune sandstone creating a convex lens shaped reservoir (Figure 73).

The debate over whether the increase in sandstone thickness is caused by basin topography or preservation of dune topography can not be easily determined. The strata above and below the sandstone are laterally continuous and of even thickness thus providing no clues to the problem (Figure 72). There are some sandstone clasts in the upper deformed sandstone of the Inga which have been interpreted in other ancient sandstones as a result of debris flows down the slopes of dune crests and into the dune lows (Tewes and Loope, 1992). It has also been interpreted that aeolian sands are only preserved if they accumulate



A
WEST
16-26-87-24W6
10E PAC INGA
K.B. 2856Ft.
16-25-87-24W6
TEXACO S INGA
K.B. 2900Ft.
6-30-87-23W6
10E PAC INGA
K.B. 2776Ft.
GR
0
150
SONIC
Coplin Anhydrite
Coplin U/C
Deformed
Sandstone
Facies
Inga Sandstone
Margin of Field


6-30-87-23W6
10E PAC INGA
K.B. 2776Ft.
SONIC
150
6-29-87-23W6
10E PAC INGA
K.B. 2696Ft.
0
GR
150
SONIC
6-28-87-23W6
10E PAC INGA
K.B. 2755Ft.
0
GR
150
SONIC
6-27-87-23W6
10E ET AL INGA
K.B. 2550Ft.
0
GR
150
SONIC
Coplin Anhydrite
Coplin Dolomite
Sandstone Thickening
Inga Sandstone
Margin of Field
Deformed
Sandstone
Facies

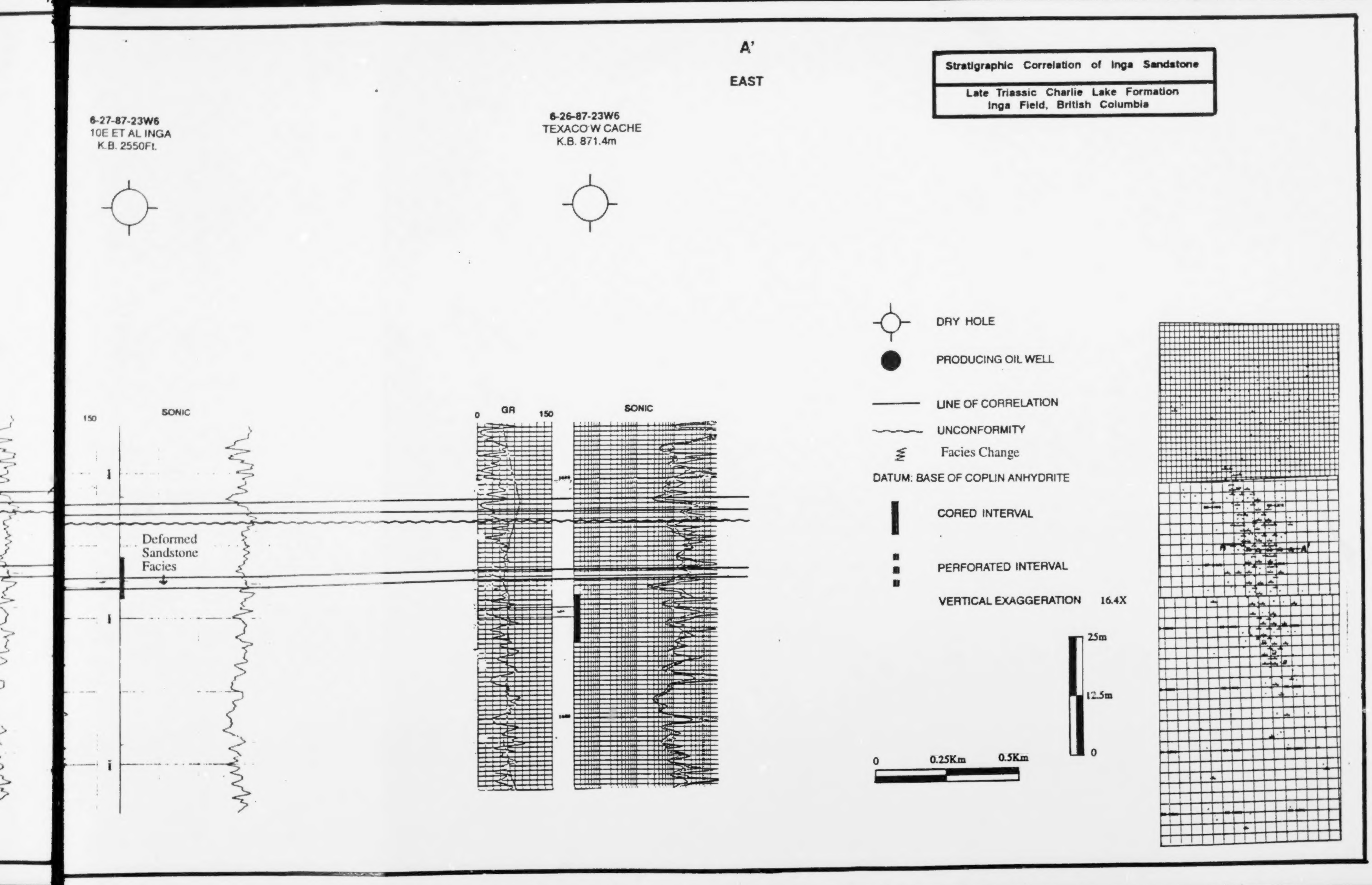

A'
EAST
Stratigraphic Correlation of Inga Sandstone
Late Triassic Charlie Lake Formation
Inga Field, British Columbia
6-27-87-23W6
10E ET AL INGA
K.B. 2550Ft.
6-26-87-23W6
TEXACO W CACHE
K.B. 871.4m
150
SONIC
0
GR
150
SONIC
Deformed Sandstone Facies
DRY HOLE
PRODUCING OIL WELL
LINE OF CORRELATION
UNCONFORMITY
Facies Change
DATUM: BASE OF COPLIN ANHYDRITE
CORED INTERVAL
PERFORATED INTERVAL
VERTICAL EXAGGERATION 16.4X
25m
12.5m
0
0
0.25Km
0.5Km
A
A'

Figure 72. Well log stratigraphic cross-section (A-A') through the Inga oilfield. Note the variable thickness changes in the Inga Sandstone and the constant thickness of the overlying and underlying lithologies.

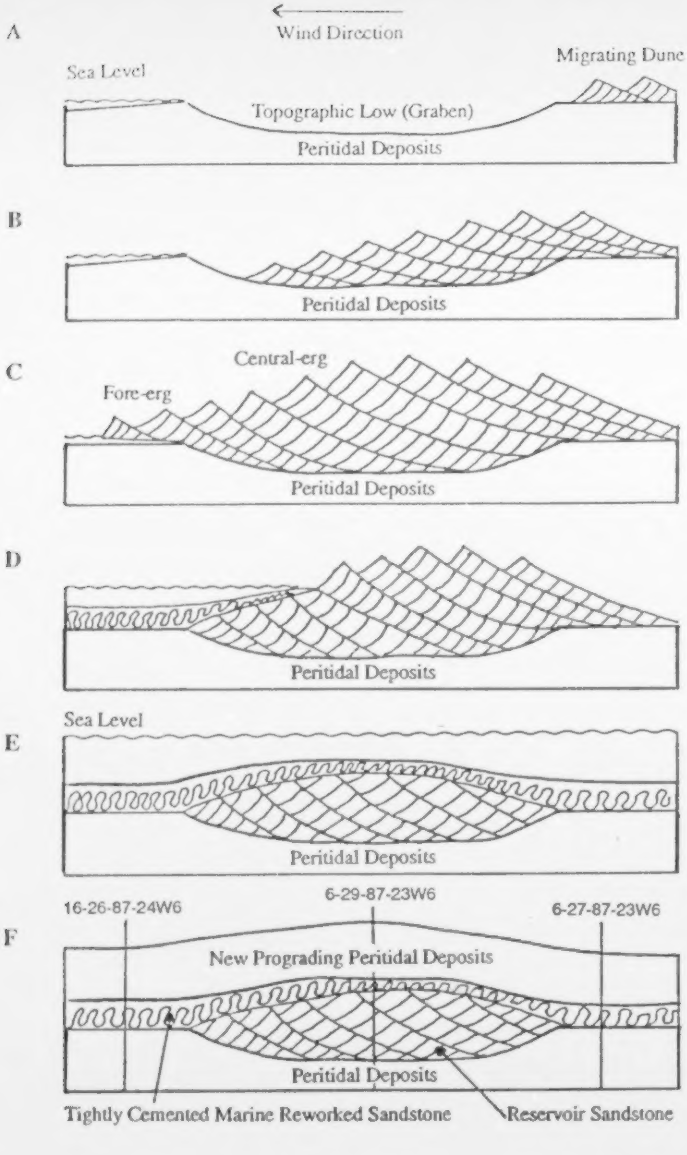

A
Wind Direction
Migrating Dune
Sea Level
Topographic Low (Graben)
Peritidal Deposits
B
Peritidal Deposits
C
Central-erg
Fore-erg
Peritidal Deposits
D
Peritidal Deposits
Sea Level
E
Peritidal Deposits
16-26-87-24W6
6-29-87-23W6
6-27-87-23W6
F
New Prograding Peritidal Deposits
Peritidal Deposits
Tightly Cemented Marine Reworked Sandstone
Reservoir Sandstone

Figure 73. Depositional history of the Inga Sandstone reservoir. (A) Initial migration of aeolian dunes across the sabkha coastal plain. (B) Initial filling of the topographic low by the migrating aeolian dunes. (C) Complete filling of the basin causing continued progradation of the dunes seaward. (D) Sea level rise which reworks the fore-erg deposits and the top of the front of the central-erg deposit. (E) Complete transgression of the Inga sandstone depositing a tightly cemented marine reworked sandstone over the preserved porous aeolian sandstone. (F) Renewed seaward progradation of peritidal deposits over the Inga reservoir. Representative of cross-section A-A' in Figure 72.

in basins (Wilson, 1971), therefore the thickness buildups of the Inga and other Charlie Lake aeolian sandstones are probably a combination of both basin lows and dune highs.

11.0.0 CORRELATION OF CHARLIE LAKE FORMATION STRATA FROM THE INGA RESERVOIR TO THE BROWN HILL SECTION

Strata of the Charlie Lake Formation is correlated from the Inga reservoir area at well 10-25-88-24W6 to the Brown Hill section on Williston Lake for several stratigraphic purposes. The first is to understand the relationships between the contacts of the Charlie Lake Formation. The second is to determine where the sandstone (aeolian) horizons occur within the Charlie Lake Formation and to trace the lateral extent of the sandstones to determine their termination point. Finally the correlation will be used to determine if any of the aeolian sandstones in the Brown Hill section have gone unidentified or undiscovered within the subsurface of the Charlie Lake Formation.

The stratigraphy of the Charlie Lake strata is best understood in the east where intensive exploration provides an abundance of core and geophysical logs. The Charlie Lake stratigraphic horizons in the east are defined on oil producing intervals which, in ascending order, are the North Pine B, North Pine A, Inga, Farrell, Coplin, Boundary Lake, Nancy and the Cecil. Due to the Coplin unconformity, strata is added to the Charlie Lake Formation towards the west providing additional oil producing horizons above the Farrell known as the Blueberry and Kobes. Cores have determined the North Pine A and B, Inga, Farrell, Blueberry and Cecil to be of aeolian origin while the Kobes, Coplin, Boundary Lake, and Nancy are of carbonate and evaporite precipitate origin. Sandstones in adjacent wells are determined by similar gamma ray signatures and from density logs that span the entire Charlie Lake interval. The use of density logs are explained in the methods section of chaper 1.

The various lithologies of the stratigraphic section are deposited as thin laterally continuous beds as shown in figure 74 making it easy for correlation and recognition of unconformities. The laterally continuous nature and the depositional origin of the anhydrites make them suitable time markers. The sandstones, sabkhas, and intertidal carbonates are diachronous in nature and therefore can not be used as a datum. The Coplin anhydrite is thus used as a datum for the section as its evaporitive signature is easy to recognize on the logs (Figure 74).

Charlie Lake strata are erosionally reduced towards the east. Two major unconformities which are responsible for the removal of strata are the Coplin and Boundary Lake unconformities which divide the Charlie Lake into three depositional units. The Coplin unconformable surface is depositionally important because it truncates an abundance of underlying aeolian sandstones thus removing potential reservoirs towards the east.

The sandstone, siltstone, carbonate and evaporitic sequence of the Charlie Lake Formation overlies sandstones and mudstones of the barrier shoreline and back-barrier deposits of the Halfway Formation (Figure 75). In the east (10-25-88-24W6), the basal unit of the Charlie Lake Formation which underlies the Coplin Unconformity, consists of a basal anhydrite dominant succession capped by an aeolian sandstone abundant succession (Figure 75). The middle unit which lies between the Coplin and Boundary Lake unconformities is an anhydritic dominant succession (Figure 75). The upper unit which lies above the Boundary Lake unconformity consists of an carbonate/anhydritic succession with an intermediate sandstone abundant succession (Figure 75). The Charlie Lake strata is overlain by dolostone dominant deposits of the Baldonnel Formation (Figure 75).

In the west, the Charlie Lake succession changes at the base, middle and top. At the base, the anhydritic dominant succession is missing and is replaced by a thicker aeolian sandstone abundant succession beneath the Coplin Unconformity (Figure 76). The aeolian sandstone succession is thicker due to less erosion in the west beneath the Coplin Unconformity. The middle unit, between the two unconformities, remains the same except for the addition of a capping shale succession which has been erosionally removed in the east (Figure 76). The upper unit is similar to the eastern strata except for that the upper carbonate/anhydritic succession is replaced by dolostone (Figure 76).

The lateral facies change in the basal Charlie Lake unit is due to the conformable relationship with the Halfway Formation. The Charlie Lake strata are back-barrier deposits of prograding parasequences of the Halfway shoreline (Willis, 1992). As deposition continues the Halfway shoreline moves up-section relative to the Charlie Lake Formation. As one moves further west, more of the base of the bottom Charlie Lake unit disappears from the facies transition, while at the same time, strata is added to the top of the unit by the climbing nature of the Coplin Unconformity up-section. This means that the Charlie Lake strata including the aeolian sandstones terminates upon progradation to the shoreline. The termination of the aeolian sandstones at the shoreline indicated on the section (Figure 74) is consistent with the prograding aeolian sequence interpreted in core.

The addition of the shale succession to the top of the middle Charlie Lake unit occurs between well C-32G 94-B-8 and well A-65-C 94-B-8 (Figure 74). The shale has been eroded in the east and is marked by the Boundary Lake unconformity. The appearence of the shale also occurs with a change to steeper dipping strata of the lower Charlie Lake unit. The appearence of the shale and the change in dip of the strata may be due to the formation of a deeper basin to the west. This basin may be a graben associated with the Fort St. John Graben complex.

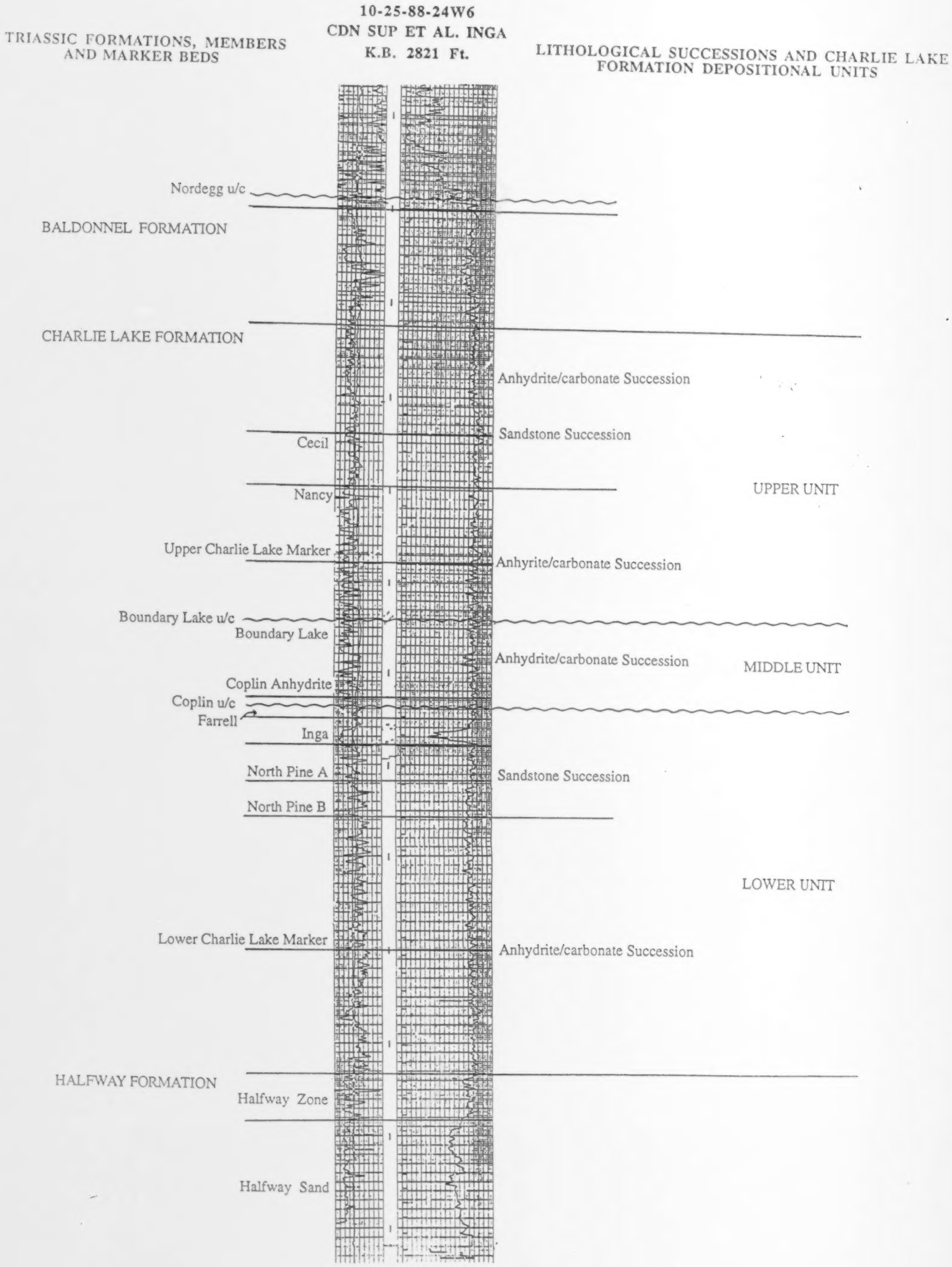


Figure 75. The members, marker beds and strata of the subsurface Charlie Lake Formation at well location 10-25-88-24W6 at the Inga oilfield used to divide the Charlie Lake into depositional sequences and units in the east.

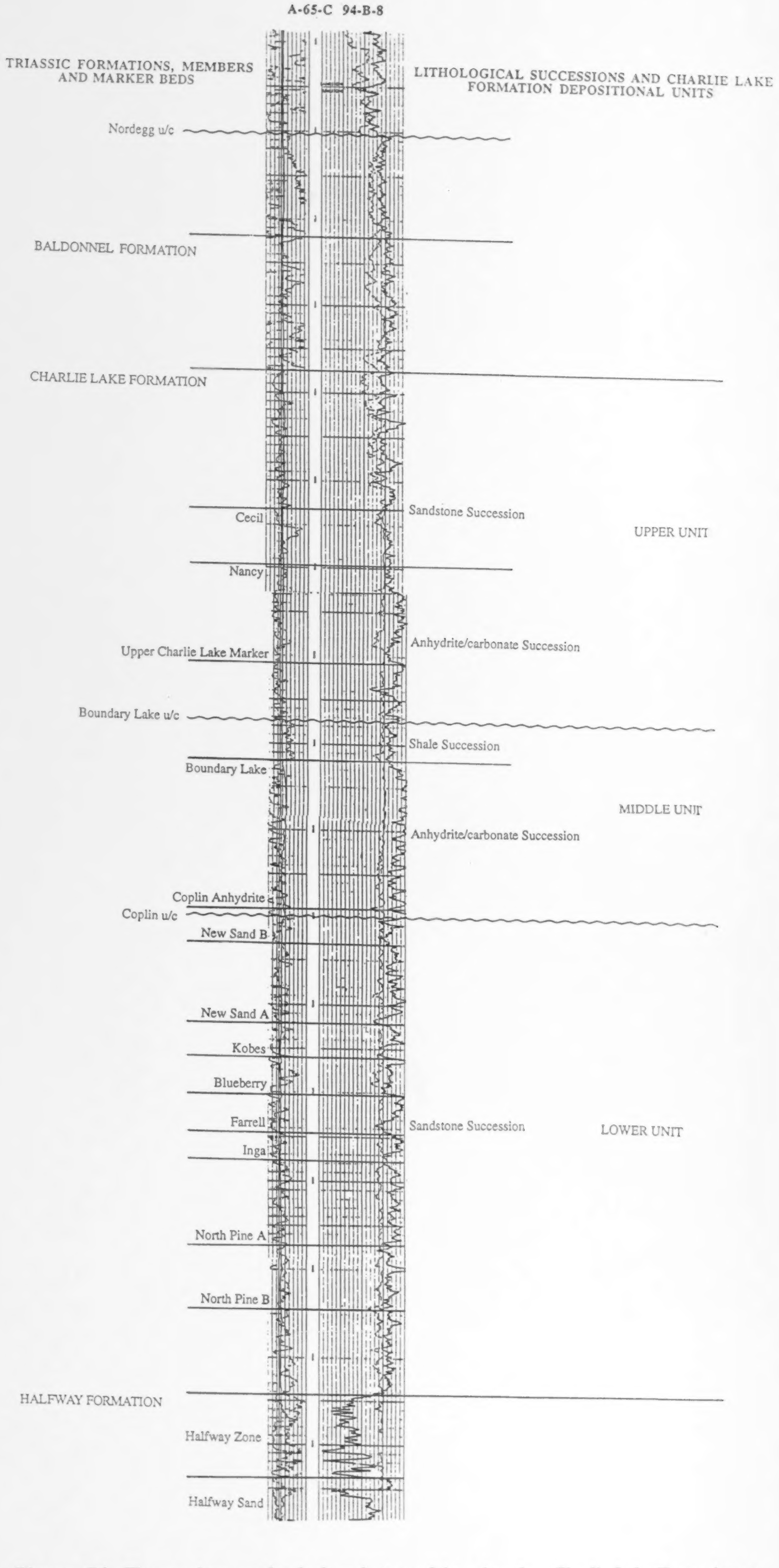


Figure 76. The members, marker beds and strata of the subsurface Charlie Lake Formation at well location A-65-C 94-B-8 used to divide the Charlie Lake into depositional sequences and units 60km southwest of well 10-25-88-24W6 in Figure 75.

The lateral facies change in the upper Charlie Lake unit is due to the conformable relationship with the Baldonnel Formation. The upper Charlie Lake strata are shallow water deposits of the deeper water retrograding parasequences of the Baldonnel sea. As the Baldonnel sea rises the deeper water carbonates of the Baldonnel move up-section over the Charlie Lake strata. The Charlie Lake strata therefore wedges out towards the west due to the Halfway shoreline moving up-section and the Baldonnel Formation moving down-section in this direction (Figure 74). As the section moves west, the upper anhydritic successions of the upper Charlie Lake unit are replaced by deep water dolostones of the Baldonnel Formation. As the section moves farther west to well A-40-L 94-B-1, the dolostone has moved far enough down-section that it overlies the intermediate sandy succession of the upper Charlie Lake unit (Figure 74).

The correlation of the Brown Hill section to the Charlie Lake Formation subsurface is a little troublesome due to the removal of the anhydrites and creation of the solution breccias. The removal of the anhydrites, removes the markers that aided in the correlation. As well, the creation of the solution breccias vastly reduces the original thickness of the Charlie Lake strata.

The Brown Hill section was originally deposited even further west than its present location but brought eastward by thrust sheets during the Cordilleran orogeny. The sandstones of the Brown Hill outcrop occur throughout the section from the base to the top of the Charlie Lake interval. In the subsurface, there are two sandstone horizons widely displaced in the Charlie Lake strata. These horizons are the upper succession of the lower Charlie Lake unit and the intermediate sandstone succession of the upper Charlie Lake unit in well 10-25-88-24W6 (Figure 75). In the subsurface, the Charlie Lake strata wedges out westward due to the Halfway shoreline moving up-section and the Baldonnel Formation moving down-section. At well A-65-C 94-B-8, the Baldonnel was deposited far enough down-section that the upper carbonate/anhydritic succession of the upper Charlie Lake unit has been removed so that the Baldonnel dolostones now overlie the intermediate sandstone succession of the upper Charlie Lake unit (Figure 74). If the Charlie Lake strata continues to wedge out westward due to the down-section migrating Baldonnel, its likely that the intermediate sandstone succession of the upper Charlie Lake unit will be removed at the Brown Hill locality. This leaves the sandstone succession of the lower Charlie Lake unit as the only possible correlative section for the sandstones of the Brown Hill section.

New sandstones are progressively appearing westward beneath the Coplin unconformity. At well A-65-C 94-B-8 two unnamed sandstones appear at the top of the sandstone dominant succession of the lower Charlie Lake unit (Figure 74). It is possible that the trend will continue and more sandstones will appear westward beneath the unconformity. The nine sandstones in the Brown Hill section are likely to be a more westward distant part of this succession. As a result, they are younger and due to erosion in the east do not extend into the subsurface Charlie Lake strata (Figure 77). This means that the Brown Hill sandstones can not be traced into the subsurface and therefore these sandstones are not likely possible subsurface exploration targets.

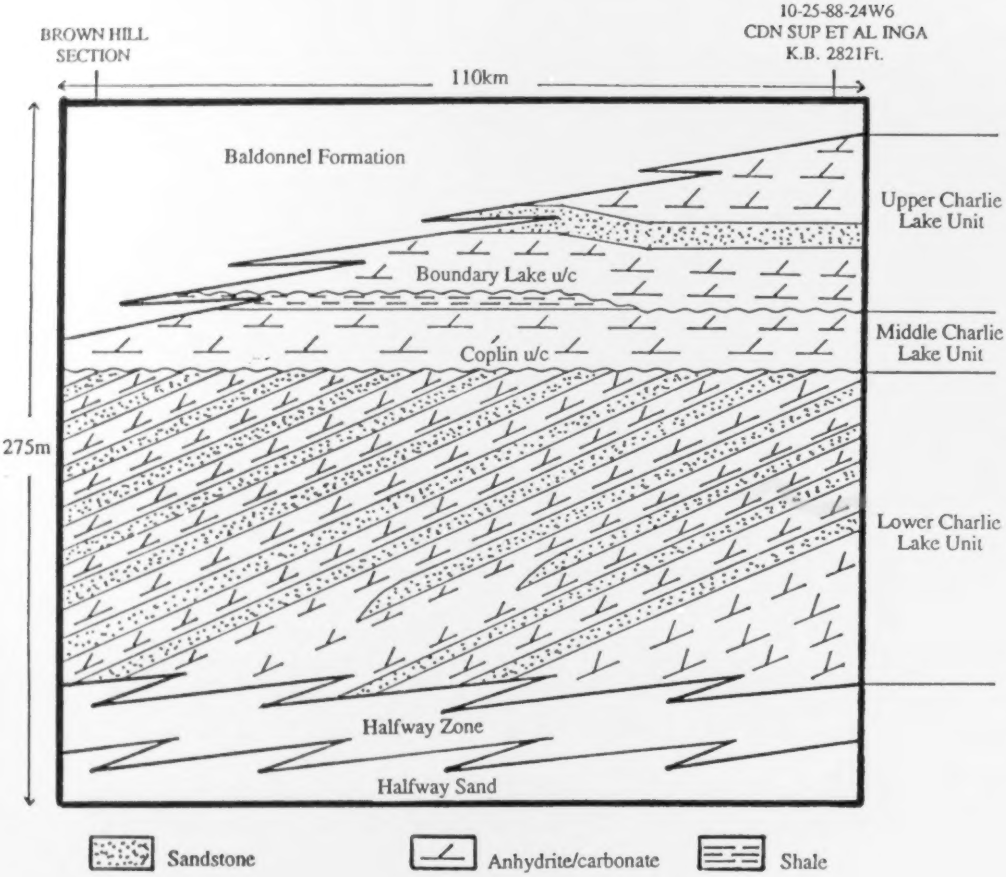

BROWN HILL
SECTION
10-25-88-24W6
CDN SUP ET AL INGA
K.B. 2821Ft.
110km
275m
Baldonnel Formation
Boundary Lake u/c
Coplin u/c
Upper Charlie Lake Unit
Middle Charlie Lake Unit
Lower Charlie Lake Unit
Halfway Zone
Halfway Sand
Sandstone
Anhydrite/carbonate
Shale

Figure 77. A generalized stratigraphic cross-section, illustrating Charlie Lake Formation lithologies and regional relationships between well location 10-25-88-24W6 and the Brown Hill section on Williston Lake.

12.0.0 DISCUSSION

The sandstones of the Charlie Lake Formation are oil producing reservoirs which occur sporadically within two depositional horizons in the subsurface of northeastern British Columbia. The sandstones are thin continuous sheet like deposits making them difficult targets for petroleum exploration. The sedimentology of the Brown Hill outcrop section and the Inga interval of the subsurface Charlie Lake Formation, along with the outcrop to subsurface correlation, provide some strategies for exploration of additional sandstone reservoirs.

12.1.0 Modern and Ancient Analogues

The aeolian sandstones and strata of the Charlie Lake Formation are similar to modern and other ancient arid coastal settings but also possess depositional features which make them unique. Modern shorelines in arid regimes combining aeolian dunes include the Segre del Negro and the Persian Gulf. The size of the dune fields are the same but the extent of the coastal plain that the ergs are migrating on are much smaller. Perhaps in time coastal plains such as the Trucial Coast, will continue to prograde seaward creating a similar broad, laterally extensive flat of peritidal deposits characteristic of the Charlie Lake strata.

There are many ancient aeolian sandstone formations, such as the Tensleep, Minnelusa and the Morgan Formations that were deposited in an arid coastal setting. The size of the coastal plain that they prograded on are similar in size and extent of the Charlie Lake coastal plain, but the sand supplied to these erg systems far exceeded the small sand amount being supplied to the Charlie Lake ergs. The large sand supply makes them easy targets for exploration as well it makes them difficult to completely rework during transgressions preserving dune structures and topography. Thus the depositional conditions of the Charlie Lake Formation sandstones are unique and warrant an exploration model exploiting these characteristics.

12.2.0 Outcrop to Subsurface Correlation

The outcrop to subsurface correlation was designed to determine which, if any, of the Brown Hill sandstones extend into the subsurface providing possible additional and unknown potential sandstone reservoirs. Originally the cross-section was constructed to determine where the outcrop sandstones laterally correlated into the subsurface. However, upon completion it revealed two other important depositional aspects which aid in the exploration for these sandstone reservoirs. Geophysical logs and a few cores have shown there are two sandstone horizons in the subsurface Charlie Lake Formation. The lower sandstone horizon occurs beneath the Coplin Unconformity and the upper horizon occurs near the top of the Charlie Lake strata. The cross-section shows the Charlie Lake strata wedgeing out towards the west due to the Halfway shoreline deposits moving up-section at the base and by the Baldonnel dolostones moving down-section at the top. This is significant, because if the Baldonnel dolostones continue to move down-section towards the west, eventually the upper sandstone horizon in the Charlie Lake Formation will be replaced by dolostones leaving only the lower sandstone horizon exposed to the west in the area of the Brown Hill section.

Additional evidence supporting the correlation of the Brown Hill sandstones to the lower sandstone horizon in the subsurface is provided by the sedimentology of the sandstones. The sandstones of the Brown Hill section display a common migration direction and are frequently flooded by marine incursions. The sandstones of the lower sandstone horizon in the subsurface, such as the Inga and Artex, also display these features. These sedimentological characteristics may be common to sandstones of the upper sandstone horizon, however, these sandstones were not examined, therefore this similarity can not be verified.

In the subsurface, erosion followed by renewed Charlie Lake deposition causes the sandstones of the lower sandstone horizon to pinch out due to the truncation of the overlying beds. The truncated beds are older towards the east and younger towards the west. Erosion becomes more prominent towards the east resulting in the continuous preservation of younger sandstones towards the west. The Charlie Lake sandstones of the Brown Hill section are the continuing trend of depositionally younger sandstones preserved towards the west in the lower sandstone horizon of the subsurface. This means that the Brown Hill sandstones are either the western lateral equivalents of the subsurface sandstones or they are depositionally younger sandstones that do not extend laterally into the subsurface portion of the section where they would have been removed by erosion. This means that the correlation has failed in the prospect of finding addition sandstone reservoirs.

12.3.0 Sandstone Sedimentology

The sedimentological study, however, provides information which may lead to the discovery of additional sandstone reservoirs. The detailed study of the fine sedimentary structures of the sandstones in outcrop and the subsurface determined the strata to resemble wind ripple, grainflow, and grainfall strata which are unique only to aeolian deposits (Hunter, 1977). Aeolian deposits occur in a wide variety of depositional settings which are commonly distinguished by the marginal deposits associated with them. As well, aeolian dunes have various morphologies believed to be controlled by wind patterns. Dune morphology type is important because it reveals sand migration direction, possible sediment source direction, and a reservoir hierarchy pattern which affects field development procedures.

Dune types can be determined from the distribution and proportion of aeolian stratification types in the foreset deposits as reflected on modern dune types. Cross-beds dominated by sandflow strata and dipping in the same direction are characteristic of crescentic dune forms. The frequent occurrence of interlaminated wind ripple strata with the sandflow strata involves a secondary airflow which develops when the dunes are migrating obliquely to the primary wind direction. The majority of the cross-beds in the aeolian sandstones are of this type suggesting that aeolian migration was dominated by obliquely oriented crescentic (barchan) dunes.

The sandstones are thin and this is probably reflected by the amount of sand being supplied to the dune field from the source area. In modern dune fields, barchan dune forms are the first to develop and as the sand supply increases, larger dune forms such as barchanoid ridges and linear dunes. The extreme dominance of crescentic (barchan) forms in outcrop and in the subsurface suggests that the sand supply was limited or that the larger dune forms did not have sufficient time to develop, perhaps due to the coastal depositional setting of the dune fields.

The coastal setting is concluded from three lines of evidence provided in the study. At the Brown Hill section, the Charlie Lake Formation deposits conformably overlie marine shoreline deposits of the Halfway Formation suggesting that the Charlie Lake and Halfway are stratigraphically conformable. As well, the correlation of the aeolian sandstones in the subsurface reveal that they correlate and terminate at the Halfway Zone which are back-barrier deposits of the Halfway marine shoreline. The final evidence of a marine setting is provided by the interfingering of marine carbonates and anhydrites with the aeolian sandstones.

The interpretation of arid peritidal deposits interbedded within the aeolian sandstones indicates a coastal setting influenced by tidal activity. Modern arid coastlines such as the Trucial coast are broad, low gradient plains in which the peritidal deposits prograde seaward. The Charlie Lake dunes migrated on a similar coastal plain except that the plain was much broader laterally and landward. The tidal activity and low gradient of the plain are important because a storm event or just a slight rise in sea level will flood the plain possibly terminating aeolian deposition. Evidence of marine flooding is provided by the deposition of thin laminated anhydrite beds, marine caused deformation of dune strata (facies L) and marine sandstone interbeds (facies M, U and V) within the aeolian sandstones. This means that during intervals of Charlie Lake time when the sea level was unstable (frequent rising and falling), such as the middle Charlie Lake unit positioned between the Coplin and Boundary Lake unconformities (Figures 75 and 76), the depositional sequence consisted of just peritidal carbonates and anhydrites. Aeolian sandstones were not deposited because the frequent marine flooding prevented the development of a dune field.

12.4.0 Exploration Strategies

Knowing that the aeolian sandstones are prograding seaward, Porter's (1986) erg migration model can be used to suggest exploration areas where additional aeolian sandstones may be found. If the amount of sea level rise, the pace of seaward erg progradation and a sand supply were constant throughout time, the rock record would consist of interbeds of marine and aeolian strata in which the aeolian strata would progressively prograde farther seaward in relation to a fixed point. Since eustasy does not occur in this manner, erg progradation is dependant upon the sand supply keeping pace with sea level rise. As suggested by the barchan dune forms and the deposition of thin sandstone bodies, the sand supply probably was not able to keep pace therefore the sea level rises would terminate erg deposition.

If erg systems were established during a period in Charlie Lake history when there were long pauses between sea level rises, the ergs would prograde a great distance seaward until they reached the shoreline or were finally terminated once sea level had risen. In periods when sea level rises were occurring frequently (ie., middle Charlie Lake unit), the ergs would not have sufficient time to prograde and would be terminated a farther distance landward. These types of erg deposits which were prematurely terminated by sea level rise did not have sufficient progradation time and therefore will be located in strata east of the Inga reservoir study area (Figure 78).

Evidence of the existance of ergs that were terminated early by sea level rise are shown in some cores that extended well into Charlie Lake strata above and below the Inga Sandstone. As the ergs prograded on the sabkha plains (facies O), sand blown from the fore-erg sand sheets and dunes would adhere to the sabkha surface. As the erg prograded closer, the sabkha deposits became sandier. Thus, the sabkha plain positioned ahead of the erg possesses an upward increase in sand percentage. If these sandy sabkha horizons are traced laterally landward (the direction they are migrating from) they may lead to an erg deposit which may possess reservoir quality characteristics (Figure 79).

It is suggested to examine the longer cored intervals within the Charlie Lake Formation looking for these sandy sabkha horizons. The increase upward in sand is evident on some

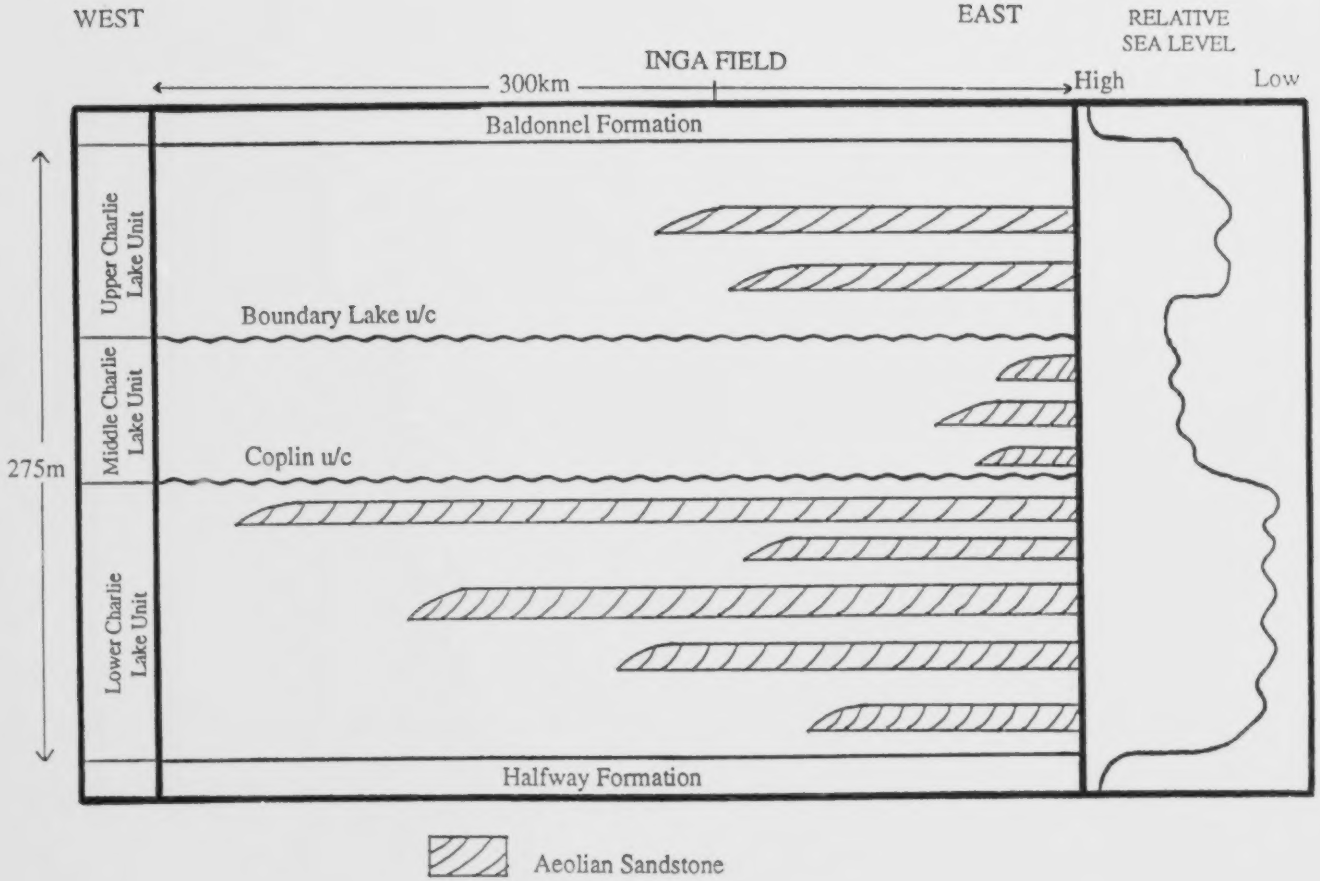

WEST
EAST
RELATIVE SEA LEVEL
INGA FIELD
300km
High
Low
Baldonnel Formation
Upper Charlie Lake Unit
Boundary Lake u/c
Middle Charlie Lake Unit
Coplin u/c
275m
Lower Charlie Lake Unit
Halfway Formation
▨ Aeolian Sandstone

Figure 78. Conceptual stratigraphic cross-section illustrating the positioning of possible aeolian sandstone reservoirs within the Charlie Lake Formation depositional units controlled by relative sea level.

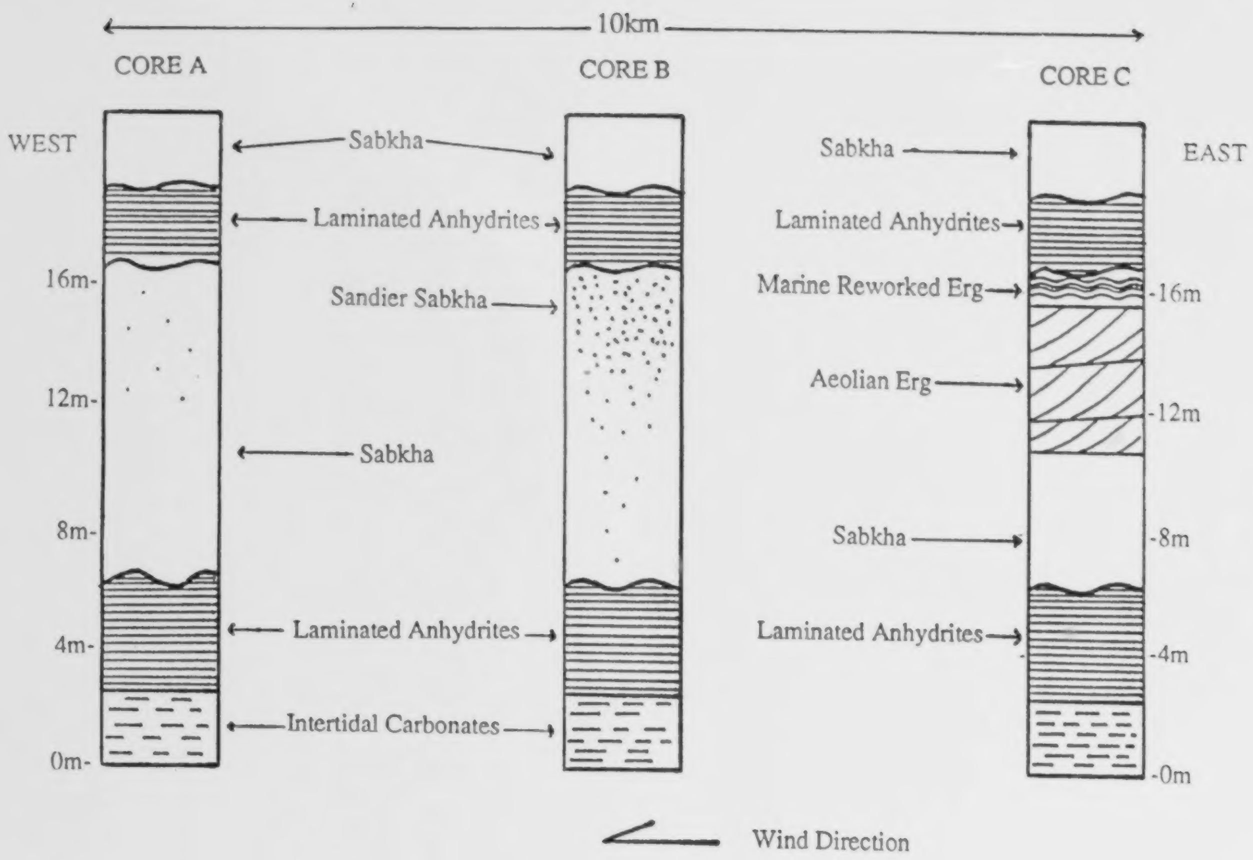

10km
CORE A
CORE B
CORE C
WEST
EAST
Sabkha
Laminated Anhydrites
Sandier Sabkha
Sabkha
Laminated Anhydrites
Intertidal Carbonates
Sabkha
Laminated Anhydrites
Marine Reworked Erg
Aeolian Erg
Sabkha
Laminated Anhydrites
16m-
12m-
8m-
4m-
0m-
-16m
-12m
-8m
-4m
-0m
Wind Direction

Figure 79. Exploration model for Charlie Lake sandstones based on erg migration on a sabkha surface. As the erg advances, the sabkha becomes sandier, therefore if such a sandy sabkha horizon is located, a thick erg deposit may be located upwind in the laterally adjacent strata.

gamma ray logs (Figure 80). If traced laterally eastward (upwind) they may lead to the discovery of a terminated erg reservoir. The ultimate conditions would exist if a few cored intervals of the entire Charlie Lake strata were drilled. Not only would this provide the location of the sandy sabkhas and erg intervals within the strata but it would also act as a stratigraphic reference for the Charlie Lake Formation.

This exploration model is only viable for the lower and possibly the middle Charlie Lake units. This is because the prograding seaward erg model of the lower sandstone horizon may not fit the aeolian origin and migration pattern of the ergs of the upper sandstone horizon as these sandstones have not been examined. Therefore an alternative model or a variance of the model may be needed for the ergs of the upper sandstone horizon.

Another exploration possibility is to examine the structural elements of the Charlie Lake Formation. The structural basins (Fort St. John satellite grabens?) act as an aeolian sand trap. The sand enters the small basin and once it is filled the sand continues to prograde seaward. The basin causes a sand build up and preserves the build up from marine transgressions creating a viable reservoir. The prograding ergs may pass through more than one graben or basin creating a "boudinage of reservoirs" within each sandstone layer (Figure 81). So it may be economical to survey the structural trends within each sandstone as this may lead to new reservoirs. The problem with this theory however, is that the grabens have very small fault displacements which probably will not show up on seismic surveys.

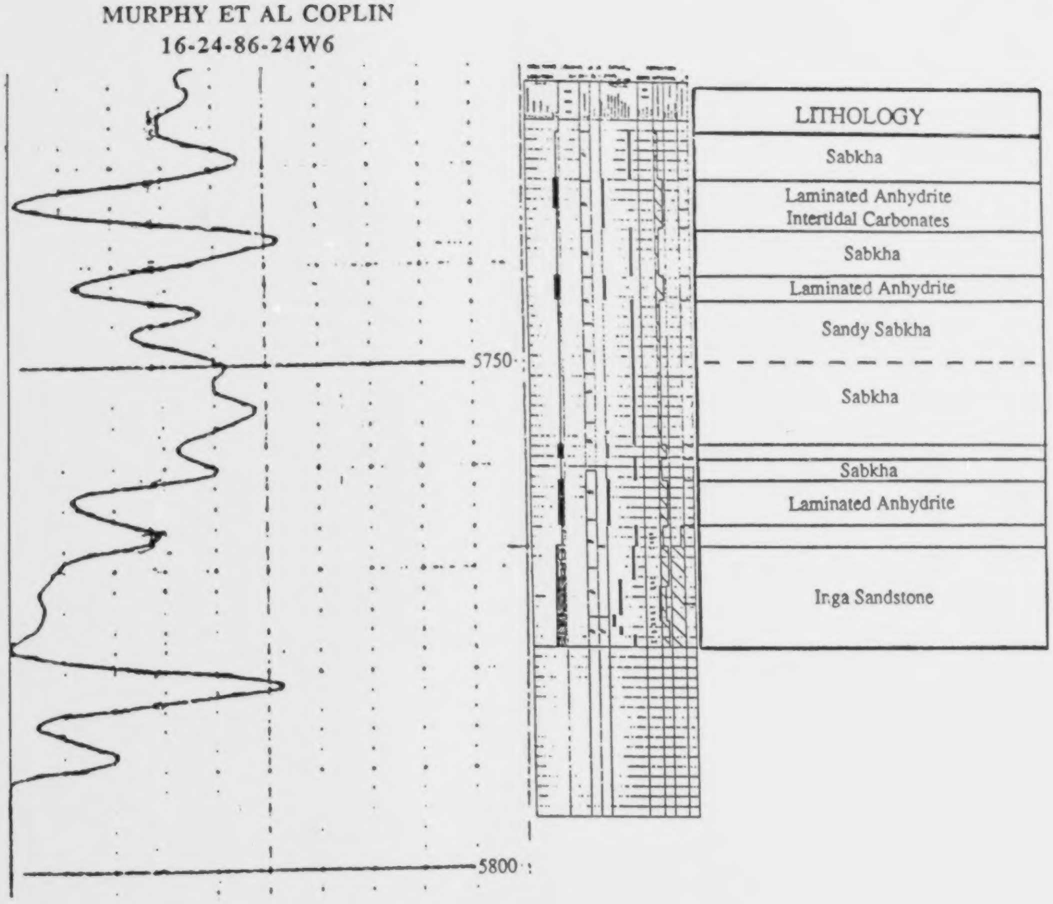


Figure 80. Gamma ray log from well 16-24-86-24W6 showing a log signature of a sandy sabkha deposit in Charlie Lake Formation strata correlated to a core description.

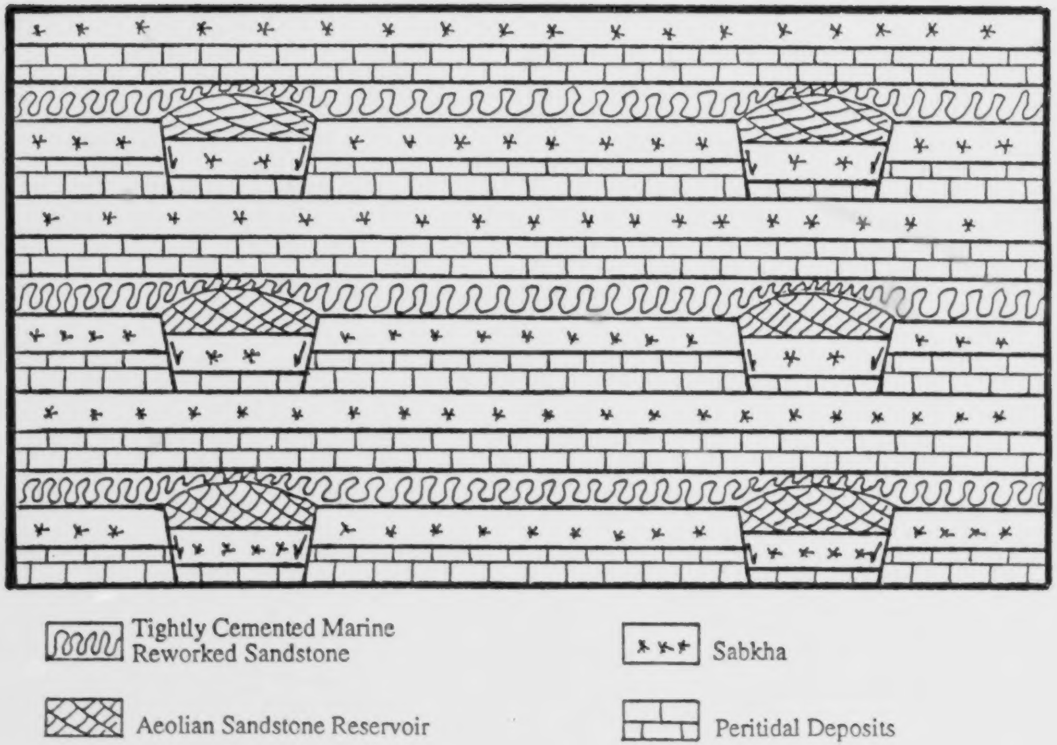

Tightly Cemented Marine Reworked Sandstone
Sabkha
Aeolian Sandstone Reservoir
Peritidal Deposits

Figure 81. Exploration model for Charlie Lake Formation sandstones based on the structural basins which trap and accumulate aeolian sand. Each aeolian erg may migrate through more than one structural basin creating several sandstone reservoirs. Each erg sandstone layer may be affected by the same structural basin creating layered reservoirs within the basin.

13.0.0 CONCLUSIONS

1) The subsurface Charlie Lake strata between the Brown Hill outcrop locality and the Inga reservoir consists of three depositional packages separated by two regional unconformities. The Coplin unconformity divides the middle unit from the lower unit and the Boundary Lake unconformity divides the upper unit from the middle unit. The lower unit consists of carbonates, anhydrites, siltstones and sandstones. The middle unit consists dominantly of carbonates and anhydrites while the upper unit is a carbonate, anhydrite, siltstone and sandstone succession. The stratigraphy establishes upper and lower sandstone depositional horizons within the Charlie Lake strata.

2) Examination of the Charlie Lake Formation in outcrop at Brown Hill and in core through the subsurface Inga Sandstone reveals an aeolian origin for the sandstones. The aeolian origin is based on the interpretation of the fine sedimentary structures which resemble wind ripple, grainflow and grainfall strata produced by present day aeolian processes. These sedimentary features are unique to aeolian deposits. The distribution and proportion of the various types of aeolian strata can be used to interpret the dune types that make up the sandstones. The cross-beds in the sandstones are dominated by grainflow strata indicating a dune type with an active slipface. The strata in the cross-beds are all orientated in the same direction suggesting a dominant unidirectional wind. Modern dune forms dominated by grainflow and lacking grainfall strata orientated in the same direction are characteristic of crescentic dune forms such as barchans and barchanoid ridges. Wind ripple strata interbedded with the toes of the grainflow strata are produced by a minor secondary wind which strikes the slipface at an oblique direction from the dominant wind causing the crescentic form to migrate obliquely.

3) The crescentic dunes are prograding seaward towards the south-southwest across a broad coastal sabkha plain. The coastal setting is inferred from three lines of evidence examined in the study. At the Brown Hill section, the Charlie Lake Formation conformably overlies the marine shoreline deposits of the Halfway Formation suggesting that the Charlie Lake and Halfway are partially syndepositional. As well, the aeolian sandstones in the subsurface reveal that they correlate to the Halfway Zone which are back-barrier deposits of the Halfway marine shoreline. The final evidence of a proximal marine setting is provided by the interfingering of peritidal carbonates and anhydrites with the aeolian sandstones.

4) A seaward prograding erg model is constructed from the succession of nine sandstones at the Brown Hill section. The sandstones increase in thickness and number of crossbed sets upwards. The lower sandstones are thin and consist of a single crossbed while the upper sandstones are thicker and consist of multiple crossbeds. This change occurs due to

the ergs successive progradation seaward. Initial erg formation consists of sand sheets and isolated barchan dunes (fore-erg). As the sand supply increases during progradation, the erg becomes dominated by multiple barchans dunes (central-erg). The limit of progradation is controlled by sand supply to the erg and by the rate in sea level rise.

5) The life of the coastal ergs are dependent upon the sand supply keeping pace with sea level fluctuations. The Charlie Lake ergs prograded seaward until the ergs reached the coastline or until a major sea level rise occurs preventing continued erg migration. The sandstones at the Brown Hill section clearly display this relationship. The lower sandstones in the section are thin due to a small sand supply to the erg. Sand supply did not keep pace with sea level rise; thus the ergs were rapidly transgressed. The upper sandstones are thicker suggesting a greater sand input to their erg systems. The geater sand input allowed them to keep pace with sea level rise thwarting termination of the erg. Termination occurs when the sand supply to the erg can not compensate for a major sea level rise. The marine sandstone interbeds within the upper aeolian deposits represent minor sea level rises which were ineffective in terminating the erg, thus allowing continued progradation of the erg body.

6) Correlation of the Brown Hill section to the Charlie Lake Formation in the subsurface reveals that the Brown Hill aeolian sandstones likely correlate to the lower aeolian sandstone horizon in the Charlie Lake Formation. The Baldonnel dolostones thicken down-section towards the west and ultimately replace the upper Charlie Lake sandstone horizon in the Brown Hill location.

7) The aeolian sandstones of the lower Charlie Lake horizon were deposited, tectonically tilted and then subaerially eroded. This results in younger sandstones progressively appearing westward through the strata. The nine Charlie Lake Formation aeolian sandstones at the Brown Hill section are the part of this continuing trend of westward-younging aeolian deposits. These nine aeolian sandstones are not present in the subsurface due to tilting and erosion in the east. The older, eastward deposited sandstones of the subsurface are replaced by the Halfway shoreline which climbs up-section towards the west. As a result, the sandstones occurring in outcrop are not potential reservoirs in the subsurface.

8) There are five reservoir facies within the Inga Sandstone. The most commonly occurring facies is the high-angle cross-bedded sandstones which also possesses the best reservoir properties (permeabilities and porosities) as a product of the aerodynamic process of deposition.

9) The aeolian sands accumulate in topographic lows, possibly associated with the Fort St. John Graben. The topographic lows protect the lower deposited sand during marine transgressions and preserve the permeability and porosity of the sand creating a potential reservoir for hydrocarbon accumulation. The marine reworked sandstone and overlying peritidal deposits are tightly cemented and act as quality-reservoir seals.

10) Five reservoir facies create a hierarchy of directionally perferred permeability as a product of their processes of deposition. This, coupled with the reservoir facies being laterally discontinueous, causes the reservoir to be compartmentalized and the fluid to have a preferred vertical migration path. Fluids prefer to flow through the high-angle cross-bedded sandstones followed by the massive sandstones, the low-angle laminated sandstones, the wavy laminated sandstones and finally the deformed sandstones.

11) Additional sandstones may exist east of the Inga Field where erg advance was terminated early during seaward progradation. The early termination is a result of rapid sea level rise after the development of the erg and its initial seaward advance. As a result, the ergs should be located landward (east) and correlate to strata in the west that displays frequent sea level fluctuations, such as the middle Charlie Lake unit.

12) The advance of the ergs may be displayed in the seaward portions of sabkha deposits. The sabkha deposits become sandier proximal to an erg margin. Therefore, if a sandy sabkha horizon is located in core or on geophysical logs they may laterally correlate paleo-landward (east) to an erg deposit possessing reservoir quality facies.

13) The aeolian reservoirs are deposited within topographic lows which may be related to active structural elements (grabens) during the Triassic Period. The ergs in their advance, may have prograded through several topographic lows, thus producing a chain of preserved aeolian reservoirs. As well, the topographic lows may have been active during each erg advance, thus creating a vertical succession of aeolian reservoirs. Thus, if a reservoir is found within a topographic low, additional reservoirs may exist in strata above and below.

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APPENDIX A.

Appendix A contains lithological descriptions of the cored Inga Sandstone intervals examined during this study.

Key to Symbols Used:

Lithology:

▤	Laminated Mud and Anhydrite	▧	High-angle Cross-bedded Sandstone
□	Siltstone	▤	Horizontal Laminated Sandstone
░	Sandy Carbonate Mudstone	□	Massive Sandstone
∞	Deformed Sandstone	▦	Carbonate Mudstone
≋	Wavy Laminated Sandstone	≈	Carbonate Wackestone

Lithological Contacts:

Gradational	– – – – –
Abrupt	———
Erosional	〰

Miscellaneous:

Lag Depoits	• • • • • •
Breccias	⬭ ⬭⬭

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FIGURE 74: Correlation of the Inga Oilfield to the Brown Hill Section

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